Data for Assessing and Improving Water Management in Colorado's Arkansas River Basin: Hydrological and Water Quality Studies

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Executive Summary: [In preparation]

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Chapter 1

Introduction

The challenge of ensuring the future viability of the critical water resources of the semi-arid Western United States, including Colorado, is escalating. Demand is increasing for the combination of municipal, industrial, and agricultural uses; new water supplies are becoming more difficult and expensive to develop; and climate change and highly variable snowpack conditions are raising concern. There is a growing group of stakeholders interested in in-stream flows for recreational and ecological purposes; pollution is reducing water usability; and population is increasing. From an economic standpoint, a viable water supply is essential for businesses, industry, municipalities, and rural agricultural communities. Moreover, some regions of Colorado, most notably headwaters communities, rely on water-related recreation including snow skiing, fishing, boating, rafting, and other water-based tourist activities to drive a significant portion of the local economy.

Detailed data collection and analysis are required to more thoroughly describe Colorado's water resource system in hope of better understanding it, both as it exists now and as it may be varying over time, to assure a practicable water future. The Arkansas River, drawing from Colorado's largest watershed (more than 28,000 mi^2), serves as a vital part of this water system. To characterize water conditions, both quantitative and qualitative, in the Arkansas River Basin, Colorado State University (CSU) has conducted studies in three representative regions – one in the mountainous valley of the Upper Arkansas River Basin (UARB), and two in the agriculturally-intensive valley of the Lower Arkansas River Basin (LARB). This report summarizes thirteen years of data from these study regions in contribution to a foundation that is needed, not only for system description, but also for developing computational models and other planning tools to assist with the difficult water management decisions that lie ahead.

1.1 Motivations and Scope of Studies in Colorado's Arkansas River Basin

In 2004, the Colorado Water Conservation Board (CWCB) began releasing the results of an on-going study called the Statewide Water Supply Initiative (SWSI) regarding the State's water resources supply and demands. In an update issued in January 2011, the study reported that from 2008 to 2050, Colorado's population is projected to nearly double, from 5.1 million to between 8.6 and 10 million people (CWCB 2011). It projected an average population growth over that period for Colorado's eight major river basins and for the Denver metro area, ranging from 71% or 1.3% annually, on the low end, to a maximum of 98% total growth or 1.6% annually (CWCB 2011). Population growth and the associated municipal and industrial (M&I) water demands are the most significant factors in the projected future water shortages. M&I water demands for the same period, even while assuming passive conservation (water savings due to reductions associated with regulatory policy changes and efficiency advancements), are projected to surge between 55% and 83% (CWCB 2011). The SWSI results called to action planners, administrators, stakeholders, and researchers to prepare to meet those projected needs.

In the Arkansas River Basin (Figure 1.1) projections show a 78% medium level population increase from 2008 to 2050 accompanied by a 63% increase in M&I water demand (CWCB 2011). The CWCB worked with basin water providers and the Arkansas Basin Roundtable (ABR) to identify and quantify water supply projects and planning processes to meet 2050 M&I consumptive needs. The categories these projects fall into are agricultural water transfers, reuse of existing fully consumable supplies, growth into existing supplies, regional in-basin projects, new transbasin projects, firming in-basin water rights, and firming transbasin water rights. The major projects identified include the Arkansas Valley Conduit, the Southern Delivery System, the Super Ditch Rotational Fallowing project, and the Preferred Storage Option Plan, including the expansion of Pueblo Reservoir. Providers and planners in the basin also are relying heavily on firming transbasin allocations to support their future supply needs (CWCB 2011). The Interbasin Compact Committee in Colorado estimated that the status quo yield success rate for projects in the Arkansas Basin is 75%. For example, a project designed to yield 1,000 ac-ft historically has yielded 750 ac-ft. Applying this yield success rate, described as realistic, to the potential yield of the identified projects and processes, an M&I water supply gap will occur in the Arkansas River Basin as early as 2035, assuming medium- level demand growth and passive conservation. Under these assumptions, the basin supply gap will total 78,000 ac-ft by 2050. Even under a scenario with all currently planned water supply projects yielding 100%, supply gaps will ensue by 2040 with an estimated 2050 shortfall of 54,000 ac-ft (Morea et al. 2011). The updated SWSI report further identifies several Arkansas River basin-specific challenges and key points with respect to water management issues and needs over the next 40 years. Throughout the basin, these include the over-allocation of available water based upon historic flows, the requirements of the Arkansas River Compact with Kansas, and the impact from recreational water rights on the development of augmentation plans for agricultural transfers (CWCB 2011).

For the UARB, the portion of the watershed upstream of Pueblo Reservoir (Figure 1.1), water management challenges are expected to center on high population growth rates (CWCB 2011) with attention to the need for new domestic groundwater wells (Watts 2005). One of the key points noted for the UARB by the SWSI update study is the challenge of obtaining augmentation water to handle the projected growth in the area (CWCB 2011). Colorado's renewable groundwater is considered part of the surface water system and requires augmentation back to surface waters when groundwater is consumed. The common sources of augmentation water are in-basin reservoir storage and agricultural transfers. Water rights are transferred from agriculture and stored for timed release to the surface water to mimic the lost contribution from the withdrawn groundwater. The transfer of agricultural water, however, threatens the agricultural economy and its regional legacy. The critical tourism economy in the region also is acquiring nonconsumptive in-channel recreational water rights to manage surface flows for recreational and environmental purposes, creating further challenges in establishing augmentation storage water. Along with a lack of comprehensive hydrologic data and the unique heterogeneous geologic characteristics of the region, understanding the interconnected groundwater and surface water flow processes in the UARB is a critical component of planning for water management futures for the Arkansas River Basin.

Specific to the LARB, the portion of the basin downstream of Pueblo Reservoir, environmental water quality and agricultural viability are key concerns, particularly related to shallow groundwater tables, excessive salt buildup, and high selenium (Se) and uranium (U) (Gates et al. 2009). Concerns over the impact on rural economies from agricultural transfers, suitable drinking water, and the viability of the urban economy are also key points. The SWSI report (CWCB 2011) points out that the LARB will face continued pressure over the coming decades for transfer of agricultural water rights, with accompanying decline in irrigated acreage, to meet municipal demands.

Total dissolved solids (TDS) in the Arkansas River in the LARB were reported by Miller et al (2010) to increase about tenfold from the outlet at Pueblo Dam to where the river crosses into Kansas. Shallow saline groundwater tables, created in part by inefficient irrigation and canal seepage, contribute to waterlogging and high soil water salinity in many fields bringing about significant decline in crop yields (Burkhalter and Gates 2005, Gates et al 2012, Morway and Gates 2012). All three segments of the Arkansas River in the LARB are listed as impaired for excessive Se concentrations and the segment of the river downstream of John Martin Dam is impaired for U (USEPA 2010 - http://iaspub.epa.gov/tmdl/attains_impaired_waters.impaired_waters_list?p_state=CO&p_cycle=2010 ,Gates et al 2009). In recent years, there also has been a growing concern about nitrogen (N) and phosphorus (P) pollution of groundwater and streams in the LARV.

Better management of the water resources in the Arkansas River Basin will be required to meet future increased demands. Improved management will require more data collection, analysis, and characterization of the basin water system. Toward this end, CSU launched studies in 1999 in an upstream study region (USR) of the river valley of the LARB near La Junta between Pueblo and John Martin Reservoirs (Figure 1.1). The aim was to describe the severity and extent of problems related to the irrigated stream-aquifer system of the LARB and to explore alternative solutions. In 2002, studies were extended to a downstream study region (DSR) near Lamar downstream of John Martin Reservoir (Figure 1.1). These efforts, which include field monitoring and computational modeling, have been funded by numerous local, State, and Federal agencies, listed in the Acknowledgements section.

To serve as the centerpiece for optimized water management in Colorado, planners have designated a set of data-driven Decision Support Systems (DSS), tailored for each of the State's major river basins. Each basin DSS would assist water stakeholders at private, public, and many utilitarian levels to plan for the future, adapt to changing conditions, weigh possible effects of water exchanges and augmentations, and help assess impacts of variable decisions to the overall hydrologic system. A DSS currently is in feasibility stages of development for the Arkansas River Basin. Data collection has been recognized as a critical component to undergird the DSS development and reach the goal of implementing a viable tool to execute better water management decisions (Brown and Caldwell 2011). Since the tool will only be as successful as the supporting data is comprehensive and accurate, beginning in 2009, with funding from the CWCB and the ABR, CSU was charged to begin work in a third study region, this one located in Chaffee County the center of the headwaters area of the UARB. The CWCB and the ABR also provided additional funding in support of the on-going CSU studies in the LARB agricultural regions.

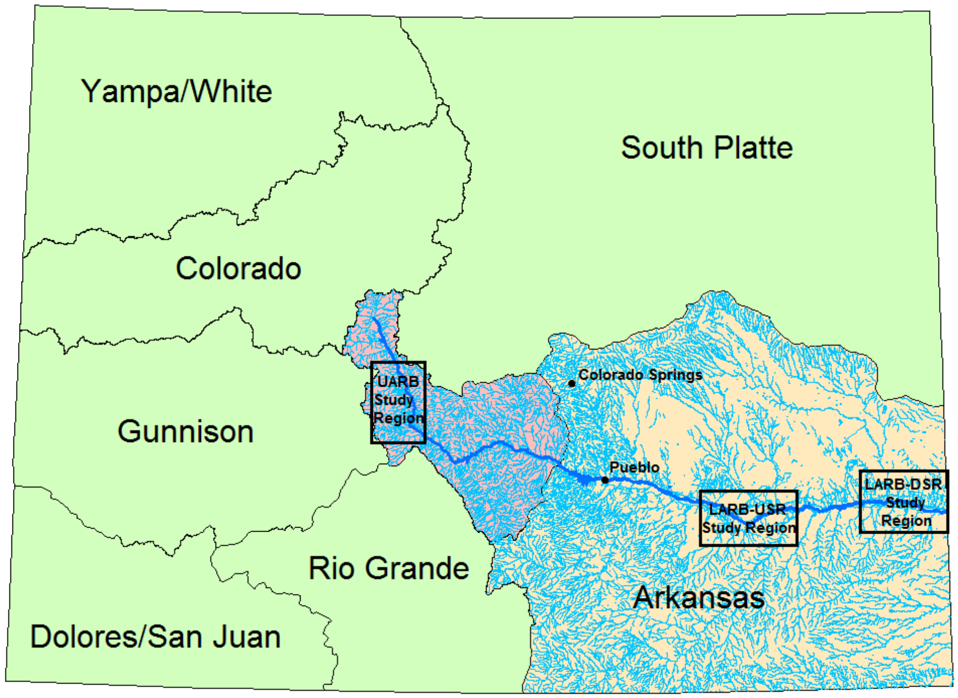


Figure 1.1: River Basins of Colorado, highlighting the Arkansas River Basin delineated by the UARB (pink) and LARB (tan) along with its hydrologic network. Locations of the UARB study region and the upstream study region (USR) and downstream study region (DSR) within the LARB are shown.

1.2 Nature and Objectives of this Report

This report aims to describe water quantity and quality characteristics derived from CSU studies in the UARB and LARB over the period from April 1999 to November 2012. Specifically, it considers selected hydrologic conditions of river and tributary flows, explores seasonal variations in river flow sources and mass load contributions to the system, examines the relationship of the shallow groundwater aquifers with surface water, and evaluates basic ground and surface water quality. The nature of the report is primarily descriptive, although some general interpretations and conclusions are drawn. Emphasis is given to more recent (2009 – 2011) activities supported by the CWCB and ABR with a view towards determining priority considerations for the proposed Arkansas Basin DSS to be developed in the near future. However, broader results from longer-term studies, especially in the LARB, are presented with references to previous reports and papers that provide further details. Throughout the report reference also is made to more detailed information that is presented on a DVD called the Arkansas River Basin Hydrologic and Water Quality (ARBhwq) CD which is available upon request or may be downloaded from the Colorado Water Institute at CSU (http://www.cwi.colostate.edu/).

The report comprises a background discussion of the study regions, the methodology of data collection, the results and analysis, and conclusions and recommendations. The focus of analysis is segregated into surface water, groundwater, and water quality. Surface water flow conditions during the study periods are compared to long-term hydrologic conditions to provide context to the results of the studies. Direct flow measurements and assessments were conducted primarily in the UARB study regions with the studies in the LARB regions concentrating on water quality. Estimates of groundwater return flow to the river system are presented and discussed for all study regions. Data from alluvial groundwater monitoring wells show annual and seasonal aquifer level changes and indicate the sensitivity to natural hydrologic conditions and to irrigation activities, including recharge from canal seepage. Examination is made of water quality in surface waters and in the shallow alluvial aquifers to assess broad indicator characteristics such as temperature (*T*) and dissolved oxygen (DO), various tested minerals, and other dissolved compounds. Solute mass loading to the river system in the study regions during the study period is addressed. Conclusions of the report address significant discoveries for system characterization and for use in DSS development and support.

Chapter 2

Upper Arkansas River Basin Investigations

2.1 Upper Arkansas River Basin (UARB) Study Region

The UARB study area, as illustrated in Figure 1.1 and pictured in Figure 2.1, is centrally located in Colorado. It lies within Chaffee County and extends about 48.5 miles along the Arkansas River from the town of Granite in the north to the confluence of the South Arkansas River in Salida in the south, containing headwaters of several major tributaries to the Arkansas River. The Arkansas River valley in the study area is characterized as an intermountain, high-altitude, semi-arid basin with ranching, recreation, small towns, and extensive national forests comprising its principal land utilizations. Elevations range from 7,000 ft near Salida to over 14,000 ft at the mountaintops. Temperatures are highly variable with elevation. Average summer highs on the valley floor range from high 60s ^{o}F to low 80s ^{o}F while winter highs range from the high 20s ^{o}F to mid-40s ^{o}F. Mountaintops may reach below freezing temperatures any time of year. The Arkansas River gage in Wellsville (Figure 2.2), which is located approximately 2.8 miles downstream of Salida, measures the discharge from a drainage basin of 1,485 square miles (CDWR 2011).

Figure 2.1: Aerial view, looking north from near Salida, of the Arkansas River valley in Chaffee County, bounded by the Sawatch (left) and Mosquito (right) mountain ranges.

2.1.1 Geologic Setting of the UARB Study Region

The Arkansas River valley in the study region is the second northernmost structural basin of the Rio Grande Rift (Chapin and Cather 1994). Tectonic rifting formed a deep structural basin bounded by normal faults, which has filled with alluvial, glacial, and other basin-fill deposits to a depth of about 5,000 ft (Scott 1975; Scott et al. 1975; Watts 2005). It is bounded by the Sawatch Range to the west and the Mosquito Range to the east (Figure 2.2). The valley narrows in the northern part of the study area where the Arkansas River winds through bedrock outcroppings that create a separation from the Leadville basin, where the Arkansas River originates. To the south, the valley is bounded by the mountains around Poncha Pass. Bedrock outcroppings also exist along the eastern flank of the valley and protrude into the path of the Arkansas River creating Browns Canyon. Rocks in the structural basin range in age from Quaternary to Precambrian. Bedrock consists of crystalline igneous and metamorphic rocks of Precambrian age (primarily granite), sedimentary rocks of Paleozoic age, and igneous rocks of Tertiary age (Scott 1975; Scott et al. 1975).

The valley floor of the study area is a relatively flat, deposit-filled intermontane valley (Figure 2.1). The fine-grained basin-fill deposits, of Tertiary age, are called the Dry Union Formation. This formation underlies the uppermost glacial and alluvial deposits with some instances of surface outcroppings. The Dry Union Formation consists of as much as 4,600 ft of clay, silt, sand, and gravel (Crouch et al. 1984). The relatively thin overlying unconsolidated aquifers are the most productive fresh water aquifers in the basin and consist primarily of alluvial and glacial deposits. Thickness of this combined aquifer is variable and poorly defined but likely less than 500 ft (Crouch et al. 1984). Quaternary-aged glacial deposits of till and outwash in depths from 0 to 500 ft are the most common overlying material and vary widely in geologic composition. Till generally is more consolidated, poorly sorted, and includes silt and silt lenses with generally low water yield. Glacial outwash is similar to alluvial deposits. It is made up of sorted gravel, cobbles, and sand and provides higher quantities of water to wells. Alluvial deposits of Quaternary age generally are found along the river and tributary streams and consist primarily of sand, gravel, and cobbles (Crouch et al. 1984).

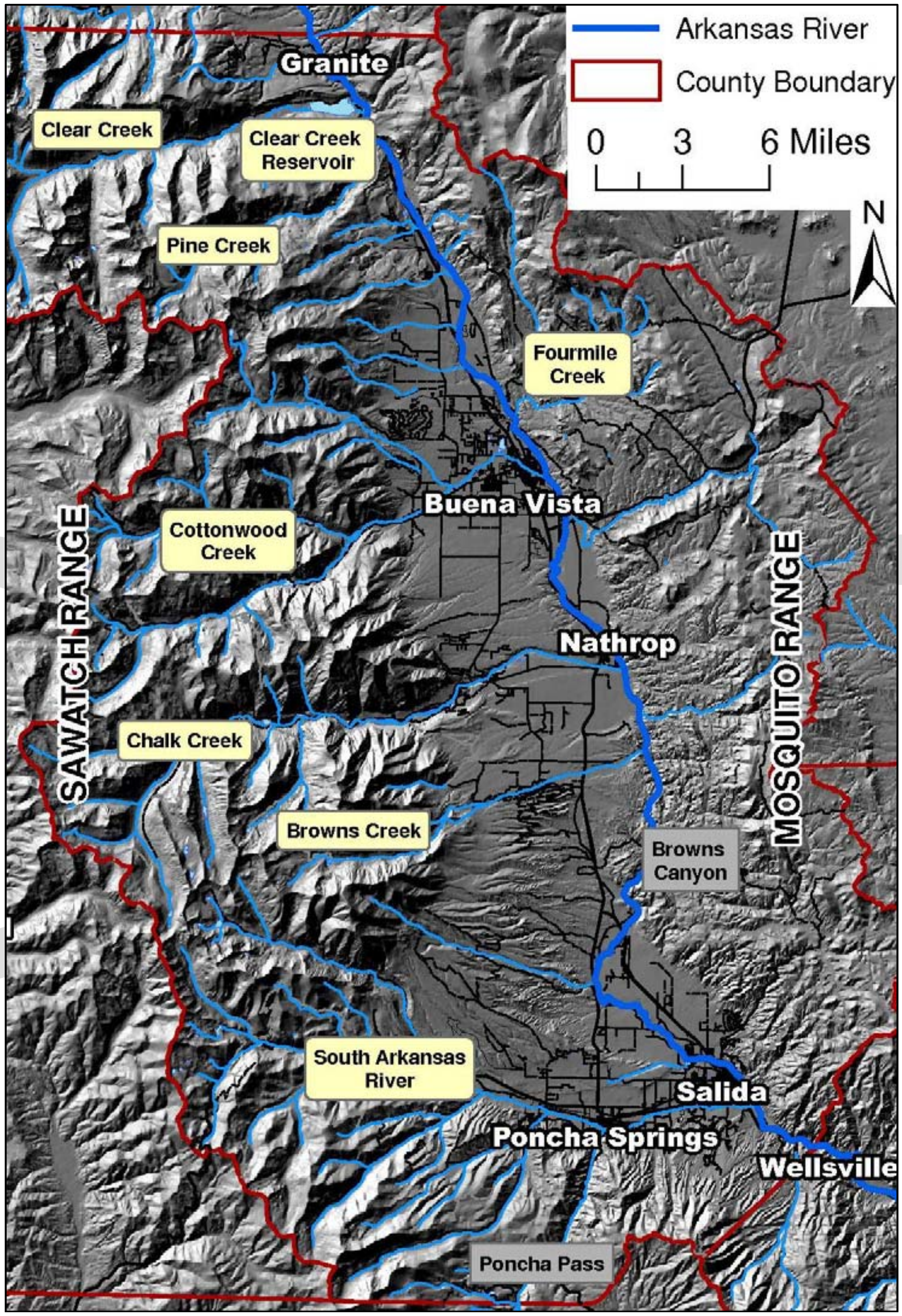


Figure 2.2. UARB study region.

2.1.2 Hydrologic Setting of the UARB Study Region

Precipitation is highly variable within the study region based in part upon latitude, elevation, and east or west side mountain ranges. On average, it ranges from about 10 in/yr on the valley floor to as much as 40 in/yr in the Sawatch Range to the west (Crouch et al. 1984). The Sawatch Range, which contains a large number of peaks in excess of 14,000 ft, separates the watersheds of the Colorado and Arkansas Rivers at the Continental Divide. Due to the high elevations of the range, orographic lifting of weather systems moving west to east deposits considerable snowpack during the winter and forms a rain shadow on the Arkansas valley and mountains to the east. On the east side of the valley is the Mosquito Range, which is much lower in elevation and receives much less precipitation. The Mosquito Range has just two peaks over 13,000 ft in Chaffee County with most of the range cresting near 10,000 ft. Within the study region, this range feeds only one small perennial stream north of Buena Vista, called Fourmile Creek.

Runoff from precipitation, primarily snow in the Sawatch Range, is the sustaining source of flow in the tributaries of the Arkansas River (Abbott 1985). Correlations between monthly average streamflow and monthly total precipitation are insignificant, but correlations between the April 1 snowpack water content and annual average streamflow are statistically significant (Burns 1985). Mean annual runoff is more than 30 in at high elevations in the Sawatch Range but as little as 2 to 5 in on the valley floor (U.S. Geological Survey 1970, as cited in Abbott 1985).

The Sawatch Range feeds the four largest perennial tributaries to the Arkansas River within Chaffee County. Listed from north to south, these are: Clear Creek, Cottonwood Creek, Chalk Creek, and the South Arkansas River. Smaller perennial tributaries include Pine Creek, Fourmile Creek, and Browns Creek (Figure 2.2). The tributaries flow across the alluvial, glacial, and basin-fill deposits of the valley floor to the Arkansas River, which is on the eastern edge of the valley. From a water-quality regulation perspective, most waters in the study area fully support their designated use classifications and portions have even been designated as “outstanding” waters (CDPHE 2009).

Figure 2.3 shows the daily average river flow during the study period from July 1, 2009 through November 30, 2011 at four gages. The Colorado Division of Water Resources (CDWR) operates the Granite, Salida, and Wellsville gages, and the U.S. Geological Survey (USGS) operates the Nathrop gage. Although storage, import, and diversion of water has changed the timing and amounts of the flows, the hydrographs still exhibit snowmelt-dominated peak flows in early summer that are about 10 times larger than the flows seen during the remainder of each year.

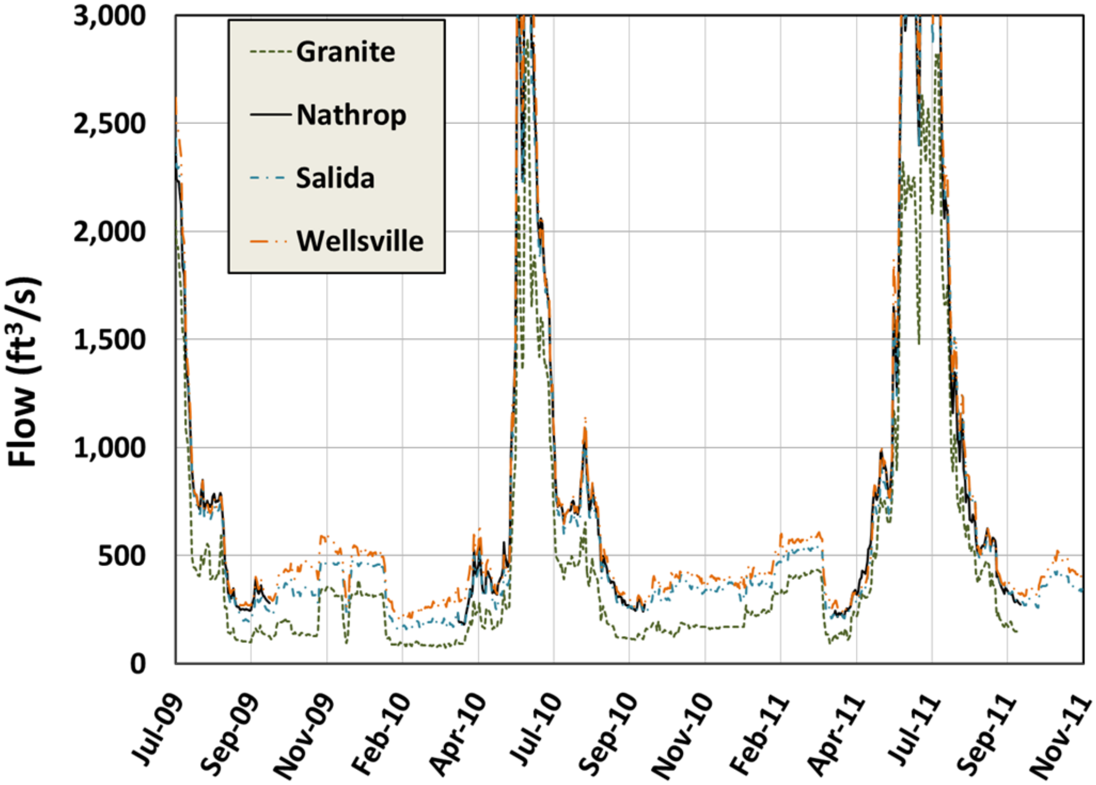


Figure 2.3: Hydrographs of daily average Arkansas River flow at gaging stations within the study region during the study period, listed from upstream to downstream.

Groundwater in the study region is acquired principally from the porous deposits of alluvial, basin-fill, and glacial materials found in the intermontane valley of the area. Nearly all water-supply wells in the UARB obtain water from the top 300 ft of the valley fill (Watts 2005) and many obtain water from the alluvial deposits at depths less than 100 ft (Crouch et al. 1984). The glacial-outwash and alluvial aquifers are the most productive and accessible groundwater supply sources. Due to their similar lithologic and hydrologic characteristics, they are considered as a single aquifer for purposes of this report, and are henceforth referred to as the alluvial/outwash aquifer. Table 2.1 presents summary characterizations of aquifers in the basin (Watts 2005).

Table 2.1: Lithologic and estimated hydrologic characterization of aquifers in the Buena Vista-Salida basin (Watts 2005).

Aquifer	*Lithologic Description*	*Porosity (Percent)*	*Hydraulic Conductivity (ft/day)*	*Specific Yield (Percent)*	*Reported well yield (gal/min)*
Alluvial / Outwash	Poorly-stratified and poorly to well-sorted silty sand and gravel. Locally contains cobbles and boulders.	15 to 40	2.8 to 1,500	12 to 34	0.01 to 1,500
Glacial Till	Non-sorted, non-stratified, moderately to firmly compacted sandy boulder tills.	10 to 20	1.6 to 98	5 to 15	0.03 to 60
Basin Fill	Unconsolidated to poorly consolidated sand, gravel, and cobbles, with interbedded coherent siltstones and friable sandstones, and volcanic ash beds.	15 to 40	0.0007 to 280	< 2 to 34	0.01 to 1,500
Bedrock	Fractured crystalline rocks.	< 1 to 10	< 130	< 10	< 1 to 10
	Unfractured crystalline rocks.	< 1 to 5	< 0.0001	< 5	< 1 to 10
	Tuff.	41	0.2	6 to 16	< 1 to 18

Watts developed preliminary two-dimensional models of vertical plane groundwater flow to evaluate conceptual models for the groundwater hydrology of the region. At two cross-sections, potentiometric lines and flow lines were computed using the groundwater model TopoDrive (Hsieh 2001, as cited by Watts 2005). The model relies on the assumption that the groundwater system is in an approximately steady-state condition. In addition, assumptions were made regarding the material's anisotropy, hydraulic conductivity, and material uniformity. The resulting conceptual model is a written and graphical description of the factors that control the occurrence and flow of groundwater in this region, such as the characteristic that the alluvial/outwash aquifer is very permeable compared to the basin-fill aquifer. Using the known boundaries, dimensions, and approximated hydraulic properties of the aquifers, the general distribution of hydraulic head and direction of groundwater flow was estimated. Watts' conceptual model suggests that groundwater flow in the permeable alluvial/outwash aquifer is generally lateral and toward the Arkansas River, while flow in the basin-fill aquifer has substantial components of vertical flow (Watts 2005). The river tributaries typically provide groundwater recharge near the mountain front, losing flow as they cross the valley floor. At the downstream reaches of the tributaries, closer to their confluence with the Arkansas River, the conceptual modeling and analysis of hydraulic gradients suggests that discharge to groundwater occurs. The Arkansas River and the South Arkansas River in particular are gaining reaches due to discharge from the regional ground-water system (Watts 2005). Watts measured water table levels four or five times per year in 92 pumping wells located in the alluvial/outwash aquifer from September 2000 to September 2003. Analysis of the observations suggests that the annual maximum groundwater table levels occur in late spring to early summer (after the peak runoff) and that minimum levels occur in early spring before the snowmelt runoff begins.

Geothermal hot springs are present along the western edge of the basin creating popular recreational resorts and ongoing evaluation for geothermal energy development. The source of the hot springs has been proposed to be a lateral offset in the western fault margins that allows surface water to seep down and heat to rise up (McCalpin 2005, as cited in Dimick 2007).

Groundwater in the upper several hundred feet of the alluvial/outwash and basin-fill aquifers is generally a calcium-bicarbonate solute composition with less than 250 mg/L of total dissolved solids (TDS) (Watts 2005). TDS is a term to describe the inorganic salts and small amounts of organic matter present in solution form in water (WHO 1996). Typically, the major cations and anions making up the TDS level are not considered contaminants, but they provide an indication of hardness and may provide information about potential contaminant sources (Watts 2005). TDS is an important component in determining overall water quality, river health, applicability for irrigation, effects on piping systems, and treatment requirements. The U.S. Environmental Protection Agency (EPA) specifies the maximum allowable TDS for drinking water as 500 mg/L (USEPA 2009), and the palatability is rated as excellent if the TDS level is less than 300 mg/L (WHO 1996).

Crouch et al. (1984) used a set of 38 groundwater samples from wells penetrating the Dry Union Formation to derive spatial patterns of TDS in the Buena Vista-Salida and Leadville basins. Figure 2.4 shows the TDS concentration contours for the Buena-Vista Salida basin that were developed by Crouch et al. (1984). Though the Dry Union Formation ranges in depth from zero up to 600 to 700 ft, most of the wells sampled were no deeper than 200 ft and in general the Dry Union Formation is hydrologically well-connected with alluvial and glacial outwash aquifers (Crouch et al. 1984). Higher concentrations tend to be located in groundwater discharge areas that were proposed by Watts (2005). As water moves through the ground, it can dissolve some of the geologic material through which it passes. This dissolution increases TDS concentrations between the points at which water enters and leaves the aquifer. Short residence times in the formations generate relatively small changes in chemical composition (Watts 2005).

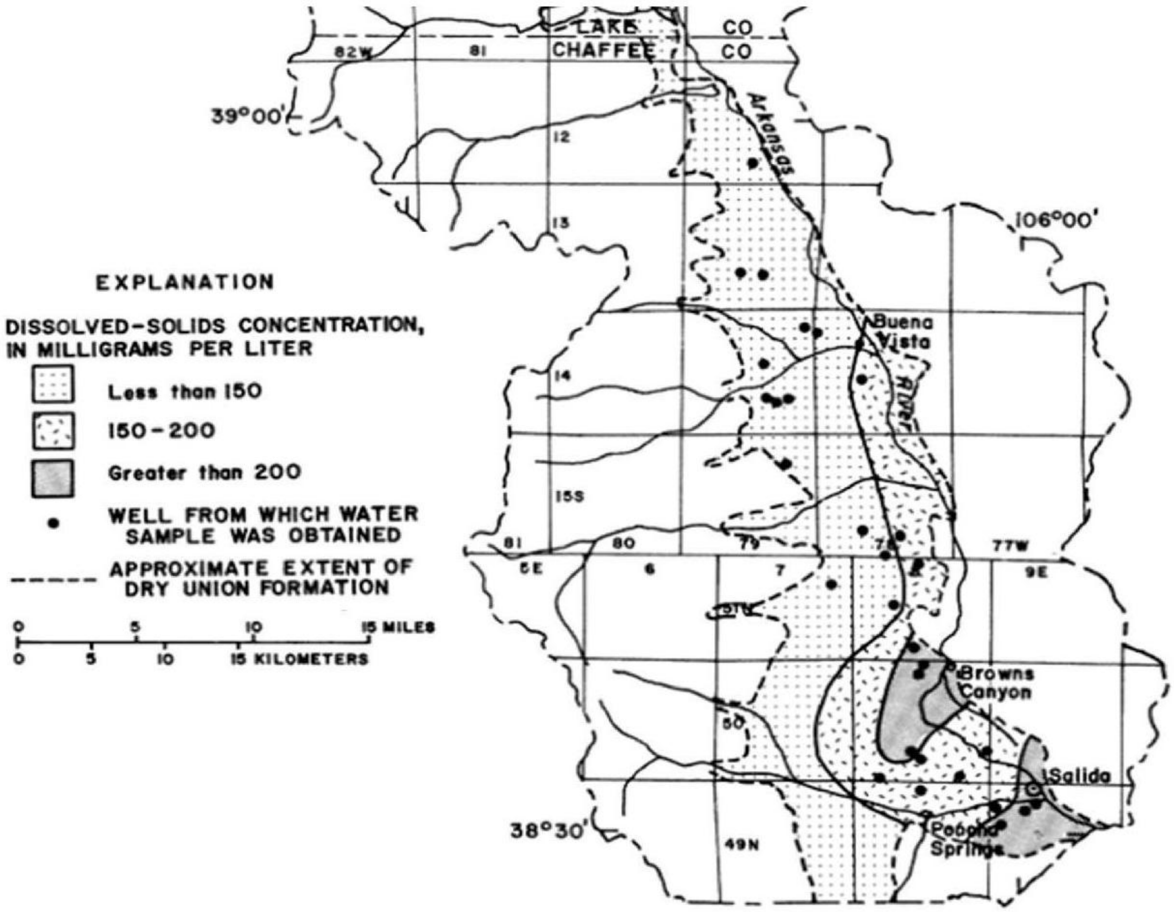


Figure 2.4: Areal variation in concentration of dissolved solids in groundwater produced from the Dry Union Formation in Chaffee County (Crouch et al. 1984).

2.1.3 Anthropogenic Factors in the UARB Study Region

U.S. Census Bureau records from 1960 to 2010 reveal the population in Chaffee County experienced irregular growth rates over the period that sum to an annual average of more than 1%, growing from approximately 8,000 to 18,000. The principal towns and their 2010 Census populations are Salida-5,236, Buena Vista-2,617, and Poncha Springs-737 (U.S. Census Bureau 2011). In October 2011, the State Demography Office forecast an annual growth rate of 1.8% through 2040, which would result in over 12,000 new county residents (DOLA 2011). Much of the future growth is expected to occur outside the utility-served municipalities and to rely on domestic groundwater wells for water. Permitted domestic wells totaling 3,443 in 2000 will surge by an estimated 4,000 to 5,000 additional wells by 2030 (Watts 2005). Municipal public water supplies for Salida and Buena Vista rely in part on surface water diversions; however, around 80% is drawn from groundwater sources (Watts 2005).

The three largest components of the economic base in Chaffee County are tourism, government, and retirees. Tourism jobs make up 24% of the local jobs (DOLA 2011). Water-related activities are at the center of the local tourism industry. Fishing, boating, rafting, and other river-based activities make the upper Arkansas River the most heavily-used recreational river in the state. The Arkansas River and its headwaters in the UARB, including Chaffee County, is a primary watershed for multiple subcategories of nonconsumptive needs, such as environmental in-stream flows and recreational flows (SWSI 2011).

Flows in the Arkansas River in the UARB are dominated by snowmelt and additionally are affected by transmountain diversions, irrigation diversions, irrigation return flows, and storage reservoirs. Transmountain diversions in the study region are limited to a small intermittent diversion called the Larkspur Ditch, which transfers at an average rate of less than 1 ft^3/s, during the summer months, from the Gunnison Basin into Poncha Creek and subsequently the South Arkansas River. Several large transmountain systems exist upstream of the study area including the Fryingpan-Arkansas system, which brings extensive water into the basin, and the Aurora-Homestake Pipeline diverting water out of the basin through its inlet at Twin Lakes.

Irrigation constitutes the largest direct diversion of surface water in the UARB. Diversions are used primarily to support ranching, including alfalfa and hay cultivation as well as irrigated pasture (Abbott 1985). Generally, management and movement of water for anthropogenic purposes result in a loss of water from the system. In addition to consumptive use, evaporation from reservoirs and during conveyance also contribute to those losses (Crouch et al. 1984).

There are many lakes and reservoirs in the basin with the largest UARB reservoirs located upstream of the study region. Reservoirs are important features that store seasonal runoff, augmentation water, and transmountain diversion water for use later in the season. The largest in the study area is Clear Creek Reservoir with a storage capacity of 11,500 AF. For comparison, the upstream Twin Lakes and Turquoise Reservoirs north of the study area have a combined capacity of over 270,000 ac-ft (CWCB 2006). Several smaller reservoirs in the study region include Boss Lake, O'Haver, and North Fork, which are located in the South Arkansas River watershed, and Cottonwood Lake and Rainbow Lake, which are located in the Cottonwood Creek watershed. These total a storage capacity of approximately 1,150 ac-ft (UAWCD 2011).

Anthropogenic factors effecting water quality include contaminants from agricultural irrigation, historic mining activities, and (to a lesser degree) industrial activity. Evaporative concentration, fertilization, and dissolution processes in agricultural irrigation increase concentrations of TDS in agricultural return flows (Gates et al 2006). A long history of mining has produced some areas of concern with respect to heavy-metal loadings. Runoff from abandoned mine tailings is the principal source of metals loading in streams of the UARB (CDPHE 2009).

Total Maximum Daily Load (TMDL) is the sum of waste loads (such as tailings runoff), background concentrations, and a margin of safety of pollutant that a water body can carry and still maintain adequate water quality for its use classifications (CDPHE 2009). Figure 2.5 shows abandoned mines and TMDL-regulated streams in the UARB. Dissolution of constituents and minerals from mine tailings, and outflow of pollutant concentrated waters from mines are typical sources of anthropogenic heavy-metals loading. TMDL-regulated streams in the study area include the 21 mi segment of Chalk Creek from its source to the confluence with the Arkansas River, and the Arkansas River through the entire study region. Chalk Creek is regulated for lead and zinc, while the Arkansas River is regulated for cadmium and zinc. All of these relate to the water quality standards for the 'Aquatic Life Cold 1' use classification.

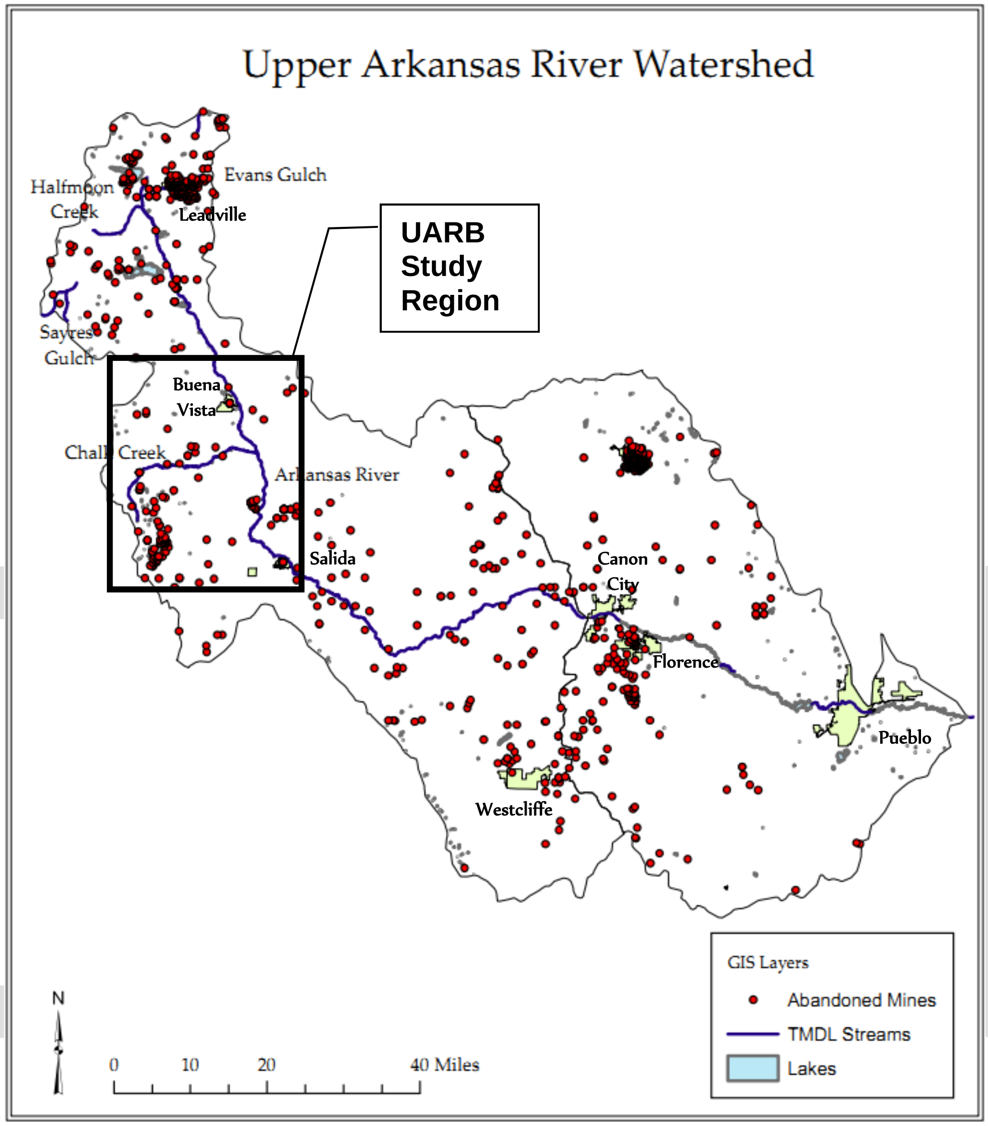


Figure 2.5: TMDL streams and abandoned mines of the Arkansas River Basin above Pueblo (CDPHE 2009).

2.2 Methodology of Data Collection in the UARB Study Region

This Section (2.2) describes the monitoring site network and data collection efforts undertaken by CSU from April 2009 to November 2011 under funding from the CWCB and the ABR to describe the basic water quality and quantity characteristics in the study region. Site selection criteria, equipment, data collection methods, quality control, and data analysis are all presented. Data collection included routine in-situ measurements of surface-water discharge, groundwater levels in the alluvial/outwash aquifer, in-situ physical and chemical water characteristics, as well as laboratory analysis of water quality samples for dissolved constituents. Discharge data were collected for analysis of temporal variability, system mass balance, and TDS load fluxes. In-situ measurements of basic water characteristics, like T and dissolved DO, were made to broadly evaluate water quality at different locations in the system and their changes over time. Laboratory analyses of water samples were made to measure the concentration of particular dissolved compounds, salts, nutrients, and elements. Additional non-routine data collection included seepage testing in irrigation canals and slug testing of hydraulic conductivity in groundwater monitoring wells.

For the surface water system, data collection sites were selected on the main stem of the Arkansas River and its largest tributaries in the study area, which are important water sources now and will be increasingly important in the future. Upstream and downstream sites were selected on the main stem and the tributaries to identify changes in discharge and water quality as flow moved through the system. Irrigation canals were selected primarily for their traits supporting successful seepage testing and being spatially dispersed over the geographical area. Groundwater monitoring wells were located within the most productive aquifer (the combined alluvial/outwash aquifer) and were dispersed throughout the study region to evaluate spatial patterns in the water table levels and water quality characteristics.

2.2.1 Surface Water Monitoring Sites in the UARB Study Region

Selection criteria for surface water sites on the main stem and tributaries started with the identification of existing and historical gage sites and finished with logistical considerations, including personnel access and the hydraulic nature of each particular site. Monitoring near historical and existing gages operated by the CDWR or the USGS allowed supplemental use of long-term datasets and offered real-time comparative flow measurements. On the main stem of the river, it also was important to create a boundary of the study area with a gage near the upstream and downstream ends of the region. This approach allowed evaluation of changes in discharge and quality through the system as influenced by the many tributaries and groundwater exchanges within the study area. Where possible, tributary sites were selected to coincide with locations planned for new gage installations by the Upper Arkansas Water Conservancy District (UAWCD). Monitoring sites at proposed new gage locations generated a valuable initial dataset for the future operator of those gages. Tributary sites located very close to their confluence with the Arkansas River were important to characterize the flows entering the main stem and the tributary contributions to the broader mass balance of the main stem. Tributary sites at upstream locations were selected to characterize the flows before they were modified by major interactions with the rift valley aquifers and/or human interventions. Logistical considerations of site selection included private property restrictions and vehicle and equipment accessibility.

Hydraulic considerations included selecting stream reaches and cross-sections that facilitate accurate flow measurements. For example, sites near man-made structures (such as culverts or bridge abutments), cascading reaches, or beaver ponds were avoided. A relatively straight and uniform stream approach with a well-defined cross-section and relatively stable bed and banks was needed to minimize turbulence and reduce three-dimensional flow complications. Figure 2.6 depicts the surface water-monitoring network and some general traits of the different sites.

All the monitoring sites along the main stem of the Arkansas River were selected to coincide with existing or historical gaging sites operated by either the USGS or the CDWR. There are five gages along the main stem in Chaffee County from the town of Granite to Salida. Table 2.2 provides a brief summary of these stations with the operating agency, period of record, and types of data available. The sites have varying periods with data and some sites only operate from April through September. Readily-available historical data range from 15-minute provisional discharge measurements to only one annual peak-flow measurement. Available historical water quality measurements range from laboratory analyses for various constituents to in-situ daily records for pH, T, and electrical conductivity (EC) (measured as specific conductance at 25^{o}C). The Salida, Nathrop, and Granite gage sites were selected for monitoring in this study (Figure 2.6). The gage at Buena Vista is no longer active, though some of the gaging structure remains in place. The upstream CDWR Granite gage was selected over the USGS gage below Granite because it had better access for measurements, was not seasonally closed, had a longer period of record, and, as the upstream boundary of the study area, allowed the Clear Creek inflow to be measured for for mass balance analyses. Finally, the Nathrop gage was included as an intermediate site.

The largest tributaries in the study region were identified through reconnaissance field work and available hydrologic background sources. For this study, routinely-monitored perennial tributaries included: (from north to south) Clear Creek, Fourmile Creek, Cottonwood Creek, Chalk Creek, Browns Creek, and the South Arkansas River (Figure 2.6). Fourmile Creek is the sole eastern tributary, originating in the Mosquito Range. All other monitored tributaries originate in the Sawatch Range to the west. One large perennial tributary, Pine Creek, was not chosen for routine monitoring due to its lack of proximity to the alluvial/outwash aquifer, its lack of anthropogenic influences, and logistical reasons. However, its flow was measured and its water quality was sampled on one occasion. In most cases, upstream and downstream sites for each tributary were identified. If the tributary forks into several branches (Cottonwood Creek and the South Arkansas River), upstream sites on each tributary were monitored. To the extent possible, the upstream sites are located upstream of the points where the tributaries enter the rift valley and upstream of any diversions. The upstream site on the north fork of Cottonwood Creek and the upstream site for Browns Creek were necessarily located within the rift valley and developed areas. The two upstream sites on the South Arkansas River (one on the river and one on the north fork tributary) were not upstream of all irrigation diversions and developed areas but were upstream of the rift valley deposits. An upstream site was not measured on Fourmile Creek due to the stream's small size and limited upstream access. Also, because it originates from the east, the stream does not cross the rift valley before entering the main stem of the Arkansas River.

Table 2.2: Historical and existing Arkansas River gage sites in Chaffee County, CO.

Station Name (ID) - from upstream to downstream	*Current Operator*	*Period of Record*	*Data Types*
Arkansas River at Granite (ARKGRNCO)	CDWR	1897 to Present	Peak Discharge, Monthly to Daily Discharge and Statistics; in-situ temperature & specific conductance 1993-Present; Aperiodic Field/Lab water quality samples 1923-2009
Arkansas River below Granite (ARKBGNCO)	USGS	1999 to Present*	Daily and Statistical Discharge; Aperiodic Field/Lab water quality samples 1999-2004
Arkansas River at Buena Vista (USGS-07087200)	None	1989 to 1993	Monthly to Daily Discharge and Statistics; in-situ water quality 1989-1993; Aperiodic Field/Lab water quality samples 1964-1993
Arkansas River near Nathrop (ARKNATCO)	USGS	1964 to Present*	Monthly to Daily Discharge and Statistics; in-situ water quality 1989-1993; Aperiodic Field/Lab water quality samples 1964-2007
Arkansas River at Salida (ARKSALCO)	CDWR	1909 to Present	Daily and Statistical Discharge; Aperiodic Field/Lab water quality samples 1978-1993

*Gage site operational April through September only

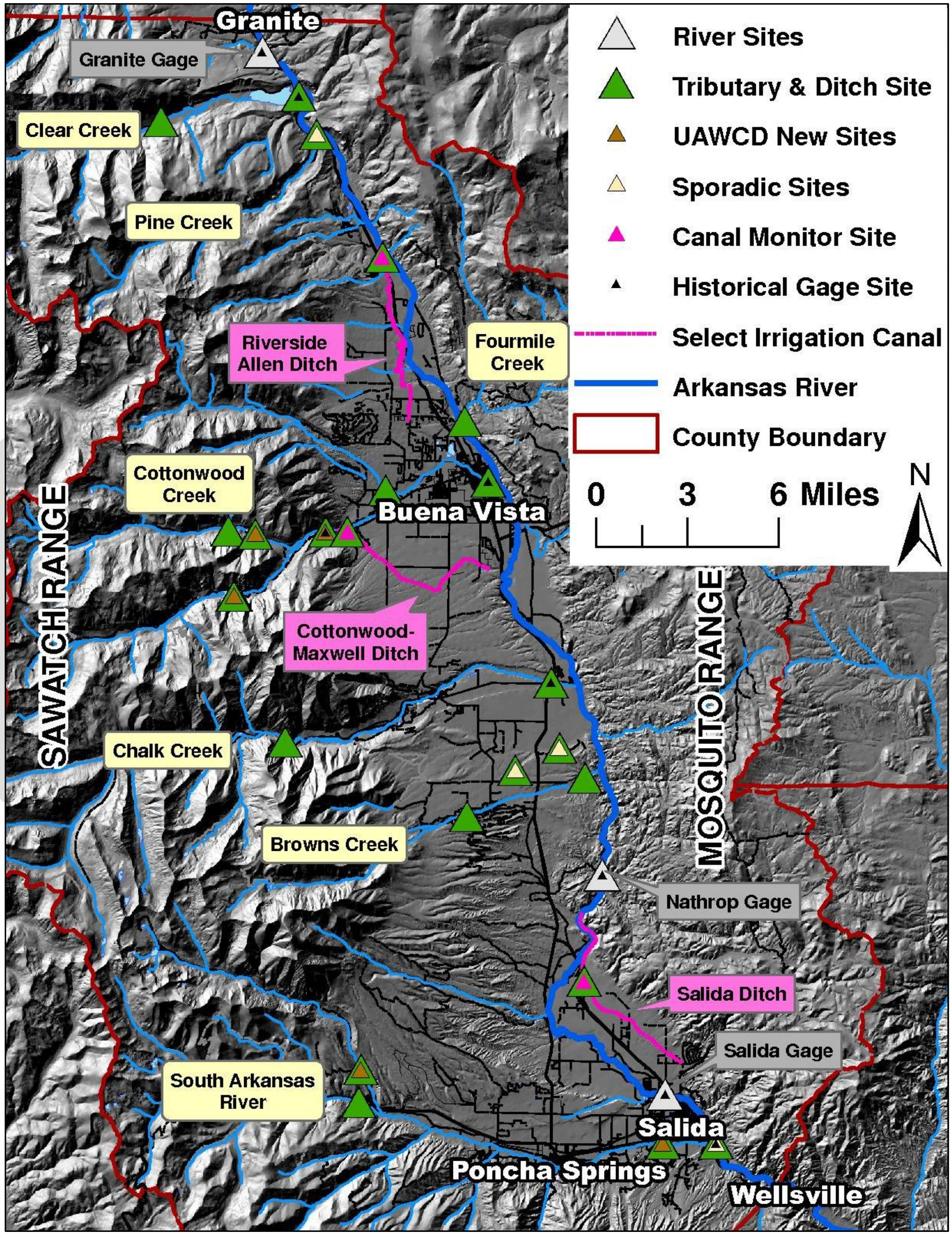


Figure 2.6: Surface water monitoring sites in the study region.

There were six existing gaging stations on tributaries at the time of site selection. Five were selected for monitoring, four of which are near each tributary's respective confluence with the main stem. The one neglected gage station site, which measures inflow to Clear Creek Reservoir, was downstream of alluvium/outwash and anthropogenic influences and was substituted with a site further upstream. Discharge measurements at the CDWR gage on the South Arkansas River were collected four times early in the study period and its water quality was sampled one time. Then, this gage was replaced by a new UAWCD gage just upstream, which was monitored for the remainder of the study. Both gages are shown in Figure 2.6. In addition, the UAWCD established four other gages, three new and one refurbished, during the 2009-2010 water year. The site of the new gage on the south fork of Cottonwood Creek was monitored from the start of the study period. As the other UAWCD gages were installed, they were added to the monitoring network for routine monthly monitoring. Four sites in the monitoring network were monitored irregularly. The South Arkansas River historic gage was monitored only early in the study period. Measurements at Pine Creek, the largest unmonitored perennial tributary in the study area, were collected near its confluence with the main stem in August 2011 to get initial comparative data and to check for water quality problems. An upstream and a downstream location on Gas Creek, an intermittent stream north of Browns Creek, also was measured and sampled one time. This measurement was spurred by the discovery of relatively high uranium (U) concentrations in a nearby monitoring well and a report from a local rancher of the presence of a “sheen” in the seep-source of Gas Creek.

At selected irrigation canals, routine monitoring was conducted near their respective headgates to estimate the quality of the water being applied to agricultural land and subsequently recharging the aquifer. Figure 2.6 shows the location of canal monitoring sites as well as the extent of the three canals selected for seepage testing, including (from north to south) the Riverside Allen Canal, the Cottonwood Maxwell Canal, and the Salida Canal. Criteria and considerations in canal reach selection include: high-priority water rights to ensure adequate flow; characteristics that are representative of regional conditions (i.e. geographical location, flow capacity, cross-section geometry, sediment characteristics, vegetative cover, adjacent water table conditions); minimal off-takes; enough length, flow volume, and likely seepage rates to be measurable within expected error; and approval, interest, and cooperation of ditch management.

The Riverside Allen Canal, located north of Buena Vista, has diversion rights from the Arkansas River of approximately 34 ft^3/s, most of which was adjudicated in 1890 with varying priority dates from 1872 – 1888. Adjudication dates and water rights for qualifying priority of flows in the canals were obtained from records of Water District 11 found at the Chaffee County Courthouse. The 4.0-mi study reach is located near the downstream end of the canal where visible seepage, convenient channel layout, and minimal off-take structures made this section well-suited for study.

The Cottonwood Maxwell Canal is located southwest of Buena Vista and runs from its off-take gate on Cottonwood Creek, southeast to the Maxwell Creek drainage. The diversion rights are for approximately 13 ft^3/s from Cottonwood Creek with an 1874 right adjudicated in 1890. There is a single landowner adjacent to this canal, which has a 3.7-mi continuous reach containing no inflows or off-takes from the headgate to the first diversion-split structure. These properties make the canal ideal for mass-balance measurements.

The Salida Canal is located in a region of the UARB known as Sand Park, which is situated just upstream of Salida on the east side of the Arkansas River. The canal diverts water from the Arkansas River within Browns Canyon in an amount up to 41 ft^3/s under 1882 – 1896 rights with adjudication in 1912 and 1897. The reach that was readily accessible for seepage testing is located in the middle to lower portion of the canal and totals 3.8 mi in length. The upper segment of this 3.8 mi reach has three irrigation off-takes and the lower segment has no off-takes.

The complete surface-water monitoring network consisted of 26 sites including: 3 main stem, 20 tributary, and 3 irrigation canal sites. A subset of 19 sites constituted the routine monitoring network while only limited measurements were collected at the remaining sites. The sites excluded from routine monitoring included Pine Creek, Gas Creek, and the canal sites (where monitoring was performed only during irrigation season). A summary of the surface-water monitoring site characteristics and Universal Transverse Mercator (UTM) coordinates are presented in Table A2.1 on the ARBhwq CD.

2.2.2 Groundwater Monitoring Sites in the UARB Study Region

The principal criterion for locating groundwater monitoring wells was the need to monitor the most productive groundwater supply in the basin (the alluvial/outwash aquifer). Other site selection criteria included: proximity to city limits, preexisting monitoring wells, and pumping wells that might affect water table levels; accessibility; cost; and landowner permissions.

The areas of alluvial/outwash deposition were identified using a digital geologic map of Colorado of 1:500,000 scale (Stoeser 2005), which was originally based on various USGS compiled maps from 1:100,000 to 1:1,000,000 scale. Higher-resolution geologic information was unavailable in digital format at the time because production of detailed 1:24,000 scale digital maps by the Colorado Geological Survey were incomplete for the area. Alluvial/outwash was found primarily in the floor of the rift valley, with limited presence among the bedrock outcroppings north of Buena Vista and in the tributary corridors above the rift valley floor. Some alluvial/outwash areas in the rift valley were excluded from consideration due to expected drill depths of over 100 ft to reach the water table. The high cost of such a deep well would reduce the number of monitoring wells that could be drilled and thus limit the areal coverage of the monitoring network. Estimated drilling depths were found through map-based analysis of well construction reports filed with the CDWR (CDWR 2009). The areas with deeper reported water tables generally were found in elevated terraces above the valley floor. Alluvial/outwash areas with water table depths expected to be less than 100 ft generally coincided with areas of active ranching and irrigation.

Figure 2.7 depicts the geographical selection criteria for the southern portion of the study region. The figure shows the alluvial/outwash areas, city limits, and buffer zones of 1640 ft (500 m) around possible water-table-influencing wells. It also shows the selected locations of the drilled wells and adopted supplemental monitoring wells. Supplemental monitoring wells were pre-existing wells with no active pumping during the study period. The construction of a network of monitoring wells is an expensive endeavor and in order to avoid collection of similar data, existing USGS and other monitoring wells in the study region were sought. Thus, the area surrounding 12 USGS monitoring wells was avoided in site selection. The Nestle Corporation™ had more than 10 active monitoring wells in the alluvial/outwash aquifer southeast of Buena Vista and east of the Arkansas River. Wells were not located in that area due to their agreement to share data. In addition, areas within city limits and within 1640 ft (500 m) of high-capacity pumping wells were avoided. High capacity pumping wells were identified by three methods: (1) CDWR wells that are not-exempt from reporting requirements, as identified by coordination with the Division 2 GIS Technician Ina Bernard, (2) UAWCD Rule-14 wells that have high pump rate and augmented wells with reporting requirements, (3) UAWCD wells with augmentation (consumptive use) of 0.2 ac-ft or more, in excess of about two ac-ft pumped annually.

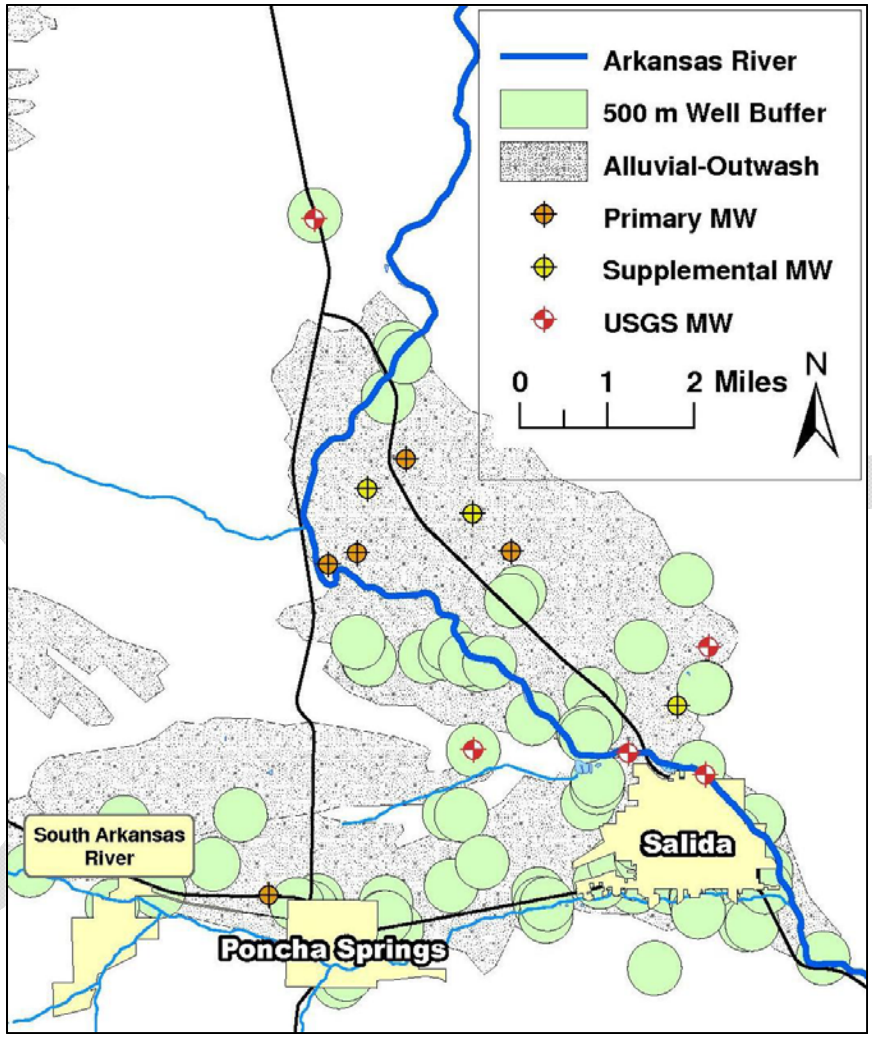


Figure 2.7: Graphical analysis of well siting areas in alluvial/outwash deposits and monitoring well (MW) locations.

Drilling method selection criteria included: a low rate of refusal from large boulders which are common in the alluvial/outwash, the ability to sample the well cuttings at 5-10 ft intervals and identify the water table when it was reached, and the preservation of the natural stratigraphy and water characteristics. The most common drilling technique for domestic supply wells in the study area is mud rotary drilling. This technique uses a mud or foam solution to help lift well cuttings and a steel casing to secure against borehole collapse, particularly in the alluvial geology. Typical drill rigs are 25 tons or greater in weight to penetrate the alluvial cobble and rock formations. By its nature, the mud rotary drilling technique introduces foreign liquids into the well borehole, pulverizes the material being drilled, and upon reaching certain depths, does not have the capability to pull the steel casing out upon well completion. Auger drilling also was considered but had a history of refusal while drilling in the cobble-filled alluvial outwash and a high possibility of borehole collapse prior to completion of the well casing installation. Consequently, a percussion-hammer drill rig in excess of 35 tons (Figure 2.8) was selected for the construction of the monitoring wells. This drill rig ensures a very low rate of refusal, sampling of largely intact stratigraphy at 5-ft intervals, protection from collapse during casing installation, and leaves no permanent steel casing at completion.

Figure 2.8: The 35-Ton dual-wall percussion-hammer drill rig.

During June 14-19, 2009, seventeen groundwater monitoring wells were constructed. The number of wells ultimately was determined by the hours of drilling that could be afforded by the project budget. The completed wells range in depth from 27.5 ft (8.4 m) to 83.5 ft (25.5 m) with an average depth of 41.5 ft (12.7 m). The CDWR *Water Well Construction Rules* (CDWR 2005) were used as a guide in the construction and regulatory requirements for the monitoring wells. Subsequently, all wells were permitted with the CDWR, including completion and submittal of well construction and test report records. Construction records include visual descriptions of stratigraphy and hydraulic conditions during drilling. Samples of the alluvium/outwash were collected at approximately 5-ft depth intervals from the drill rig discharge funnel during the drilling process. Approximately half-gallon samples were sealed and stored in 1-gallon freezer bags in the soils laboratory at CSU and could be analyzed in future research.


Figure 2.9: Completed Monitoring Well

Well construction consisted of drilling a 9 in outside diameter borehole at least 20 ft below the water table (based upon observations of saturated drill cuttings) or to the depth of any apparent restrictive clay layer (based on drill cuttings). The well casing had a 2-in nominal diameter and was schedule 40 PVC pipe meeting ASTM F480-95. The casing was machine-slotted up to the perceived water table level with a 0.020-in slot width and was fitted with a threaded bottom plug. The upper section of each well (ranging from 4 to 40 ft) consisted of solid 2-in PVC. The average depth to the slotted portion of the casing was 11.8 ft. The filter pack in the wells was variable and generally consisted of native collapse with supplemental placement of #10-20 Colorado silica sand. This silica sand is naturally rounded (it is obtained from glacial deposits), washed, kiln dried, and screened. Effective size of the sand was 0.04 – 0.06 in (1.10 to 1.15 mm). In three wells (157826-01, 500822-02, and 510810-01), a locally-procured 0.25-in, screened and cleaned pea-gravel aggregate was used after the silica sand stockpile had been exhausted. The annulus near the ground surface and adjacent to the solid well casing (top 4 to 10 ft) was filled with hydrated medium bentonite chips. Well head construction consisted of a flush-mount concrete-encased cover, a watertight lid (with a "Monitoring Hole" designation), and a locking J-plug on the top of the casing inside the access cover (Figure 2.9).

Exact well locations were determined using handheld GPS units and identifiers were assigned using a system based upon township, range, and section numbers, similar to the USGS designation system. For example, well 500811-02 is located in township 50 north, range 08 east, section 11, and the well is the second well in the section (640 acres). Table 2.3 summarizes the completion date, attributes, and locations for the constructed monitoring wells.

Table 2.3: Monitoring well identifiers, completion dates, characteristics, and locations (UTM NAD 83, Zone 13).

ID	*Date Completed*	*Total Casing Depth (ft)*	*Top of Screen Depth (ft)*	*UTM Easting*	*UTM Northing*
490804-01	6/19/2009	28.9	8.9	405079	4264280
500822-02	6/15/2009	83.7	18.4	406715	4270588
500822-01	6/15/2009	37.1	6.9	406191	4270385
500813-01	6/14/2009	69.9	40.0	409572	4270621
500811-01	6/14/2009	53.1	23.0	407626	4272324
510808-01	6/16/2009	58.4	8.2	403611	4283075
510810-01	6/16/2009	43.6	13.5	406619	4283207
157824-01	6/17/2009	27.6	7.5	406971	4287082
157823-01	6/19/2009	28.9	8.9	405674	4287866
157815-01	6/17/2009	38.4	8.5	404010	4288666
157826-01	6/16/2009	28.5	8.5	406036	4285182
147832-01	6/18/2009	28.9	8.9	400945	4294444
147925-01	6/17/2009	38.4	8.5	398713	4296108
147924-01	6/18/2009	28.9	8.9	398779	4297406
137925-01	6/19/2009	48.9	8.9	398988	4304689
137911-01	6/18/2009	34.1	3.9	397515	4310167
127927-01	6/19/2009	28.9	8.9	395411	4314390

Well development was performed immediately following well construction using a stainless steel bailer to surge water through the PVC well screen and remove fine sediment that accumulated at the casing bottom. Subsequent well development was performed in July 2009 and again in January 2010 using varying pumping methods. Generous flushing of the well was performed to establish connection to the aquifer, but some fine sediment accumulation remained in the bottom of the well casings.

To expand the well dataset, supplemental monitoring wells were added to the network. Six inactive, pre-existing wells were identified with assistance from local landowners and the UAWCD. A map showing the location of the 17 constructed wells and the 6 supplemental wells is presented in Figure 2.10.

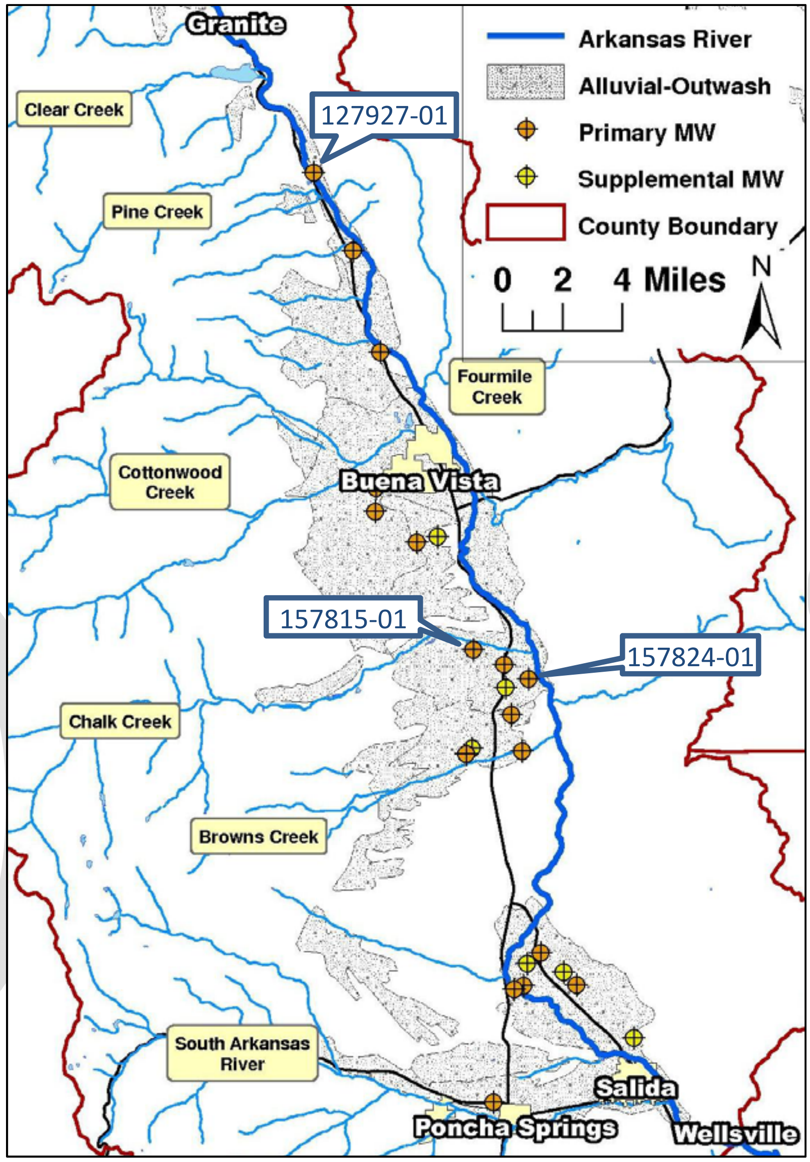


Figure 2.10: Constructed primary and pre-existing supplemental monitoring wells (MW) in the alluvial/outwash of the study region.

2.2.3 Data Collection Summary for the UARB Study Region

This section details the equipment, methods, quality control, and extent of data collection in the UARB study region. Each site was visited approximately monthly from July 2009 through November 2011, whenever conditions permitted. At surface water sites, flow rate and in-situ water quality measurements were collected. Flow rate was measured only when flow conditions permitted and typically not at sites where existing gage measurements were available. At monitoring wells, water-table levels and in-situ water quality measurements were collected. On seven occasions, water quality samples were collected from the streams, river, and wells for laboratory analysis. For the irrigation canals and monitoring wells, several tests related to characterizing the aquifer's role in the hydrologic system also were performed.

2.2.3.1 Surface Water Measurements in the UARB Study Region

The 19 routinely-monitored river and tributary sites were visited approximately every three to five weeks during the study period, for a total of 25 measurements. Irrigation canal sites were visited monthly during the irrigation season, which was April through October annually. In addition, seepage losses were measured on multiple occasions on each of the three studied canals. Seven sets of water quality samples were gathered from tributary and river sites.

2.2.3.1.1 In-Situ Monitoring of Surface Water in the UARB Study Region

Discharge measurements were taken triannually at each stream monitoring site (Figure 2.11) but were not gathered when winter weather, ice, or dangerously high flow prevented access, nor at sites with agency gages where discharge date were available. Discharge measurements were made using a *Sontek Flowtracker Handheld Acoustic Doppler Velocimeter* (ADV) ™ that uses the principle of Doppler shift of sound pulses in a volume of flowing water to determine its relative downstream velocity. Use of the ADV for discharge measurements has been found to compare with a 95% confidence level with standard USGS current meter measurements (Rehmel 2007).

Many ADV point measurements were taken across each stream cross-section, and the cross-sectional geometry was measured in the field. Each velocity measurement was applied to its respective portion of the cross-sectional area, and the total volumetric flow rate was calculated. Typical discharge measurements at a cross-section involved recording 30 to 60 individual measurements of a 30-sec averaged downstream velocity. Measurement points were determined by segmenting the cross-section width to capture no more than about 5% of the flow in any segment, which typically resulted in 25 to 30 locations. At each location on the cross-section, velocity was measured at a point 0.6 times the flow depth (for flow depths less than 1 ft) or at 0.2, 0.6, and 0.8 times the flow depth (for flow depths deeper than 1 ft). All measurement depths were measured down from the water surface. This approach is similar to methods used by the USGS (Buchanan and Somers 1969) and the USDA (Harrelson et al. 1994).

Figure 2.11: (Left) ADV device consisting of the control interface unit and the 3-pronged flow measuring transceiver, mounted on a standard USGS wading rod with offset bracket. (Right) Surface water flow measurements with the ADV on the South Arkansas River in June 2011.

At locations with existing gages, published and provisional discharge values were obtained from the agency operating the gage (either CDWR or USGS). The values from the agency records are initially considered provisional and are published as final values approximately twelve months later, at which time, gage conditions have been verified and the corresponding discharge records are amended accordingly. Published values were available and used for all gage sites through September 30, 2010. After that date, provisional discharge values were used.

During each site visit to the stream monitoring sites, EC, pH, DO, oxidation reduction potential (ORP), and *T*, were measured using a *YSI 6-Series Multiparameter Sampling System*™ (multiprobe). The multiprobe was placed in the water body to characterize flow away from the banks and away from any particularly turbulent or stagnant locations. The multiprobe was left in the water long enough for the measured characteristics to stabilize, with values recorded every 3 min until any changes were within acceptable tolerances.

The multiprobe was operated, maintained, and calibrated according to YSI recommendations and guidelines. Calibration was performed each day that data were collected starting with a visual inspection and cleaning that included cleaning the pH bulb, conductivity ports, temperature sensor, and the instrument body. Sensors for pH, EC, and DO were calibrated each day, and the ORP sensor was calibrated every 4 to 6 months. The pH calibration involved a 3-point method using solutions of pH 4, 7, and 10 with corrections made for *T*. The DO calibration considered current barometric pressure, and the sensor membrane was replaced as needed but at least every 60 days. EC and ORP were calibrated using separate reference solutions. General maintenance between sampling locations included checking the multiprobe for fouling, cleaning as necessary, and storing in wet conditions (a sealed bottle over the probe sensors with a tap water saturated sponge in the bottle).

2.2.3.1.2 Surface Water Quality Sampling in the UARB Study Region

Water quality samples were taken for laboratory analysis in July 2009, November 2009, May 2010, August 2010, November 2010, June 2011, and November 2011. A peristaltic pump with pre-cleaned 0.25-in virgin polyethylene sampling tubes and a 0.45-µm capsule filter was used to extract samples from the surface sites. Filtering was necessary for analysis of dissolved concentrations of the desired constituents. The intake of the sampling tube was placed in a flowing portion of the stream to obtain a representative sample. Each sample was taken from the filter outlet into a clean or pre-treated 120-mL or 250-mL polypropylene or polyethylene bottle. Bottles were tilted and water was directed to flow down the inside surface to reduce aeration. The sampling tubes were decontaminated for each use with 2-min washing in buckets of a dilute hydrochloric acid solution, followed by a phosphate-free detergent solution, and finally two rinse cycles in buckets of distilled water which were prepared at the beginning of each day of sampling. Sample bottles for Se, U, and the additional elements were pre-treated with a nitric acid preservative to prohibit precipitation of the elements in transit (as stipulated by the laboratory). During each sampling event, at least one distilled water sample (a blank) and at least one duplicate sample were collected and analyzed for quality control purposes. Custodial responsibility and quality control measures included chain of custody forms, labeling protocols, and temperature control from the time of sampling to the time of shipping. Samples that were sent to Ward Laboratories (PO Box 788, Kearney NE 68848) did not contain a nitric acid preservative. Upon return from field sampling, these samples were shipped to the laboratory overnight.

Surface water quality samples were gathered at tributary and river sites but were not gathered from irrigation canal sites. Laboratory analysis of the water samples included pH, sodium adsorption ratio (SAR), EC, TDS, and dissolved concentrations of sodium (Na), calcium (Ca), potassium (K), magnesium (Mg), nitrate (NO_3), sulfate (SO_4), chloride (Cl), carbonate (CO_3), bicarbonate (HCO_3), boron (B), Se, and U. For two sampling events (May 2010 and November 2010), concentrations of dissolved zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), cadmium (Cd), aluminum (Al), fluoride (Fl), and lead (Pb) also were determined.

Ward Laboratories Inc. was utilized for analysis of anions, cations, and a subset of the elements tested. Testing methods for dissolved concentrations of the focus constituents are given by the following citations: Na (USEPA 1983, Method 273.1), Ca (USEPA 1983, Method 215.1), K (USEPA 1983, Method 258.1), Mg (USEPA 1983, method 242.1), NO_3 (APHA 1992, Method 353.2), SO_4 (USEPA 1983, Method 375.4), Cl (APHA 1992, Method 325.1), CO_3 and HCO_3 (Eaton et al. 2005, Method 2330-B Titration Method), B (USEPA 1983, Method 212.3), and Fl (APHA 1992, Method 4500F^- SPADNS Method). The detection limit for most constituents is 1 mg/L. Dissolved concentrations of NO_3 and Fl have detection limits of 0.1 mg/L and 0.01 mg/L, respectively. Dissolved concentrations of Zn, Fe, Mn, and Cu were determined using a *Thermo Fisher Scientific iCAP 6000*™ series spectrometer with detection limits of 0.01 mg/L. Ward Labs participates in the Agricultural Laboratory Proficiency (ALP) and the North American Proficiency Testing (NAPT) programs for quality assurance. In addition, for every 20 samples tested, a purchased standard solution is analyzed for correlation with concentration curves, and twice daily, a locally procured sample is analyzed as a benchmark check.

Samples were analyzed for dissolved Se by the Oscar E. Olson Biochemistry Laboratories (Box 2170 Rm 133 ASC, Brookings, SD 57007) at South Dakota State University (SDSU) using test number 996.16, *Selenium in Feeds and Premixes*, Fluorometric Method (AOAC 2000). The detection limit is 0.1 µg/L. In late 2011, these laboratories were closed by SDSU for fiscal reasons, but many of the same staff moved to the South Dakota Agricultural Laboratories (SDAL). For this reason, beginning in late 2011, water samples were sent to the SDAL for analysis using the same procedures.

Test America Laboratories, Inc. (13715 Rider Trail North, Earth City, MO 63045) analyzed dissolved U, Cd, Al, and Pb concentrations using ICP mass spectrometry, method 200.8 of the EPA's *Methods for Chemical Analysis of Water and Wastes* (USEPA 1983). Laboratories in Earth City, MO and Austin, TX were both utilized, depending on their availability. The reporting limits for this method are: 1.0 µg/L for U, 1.0 µg/L for Cd, 50.0 µg/L for Al, and 1.0 µg/L for Pb. Very low concentrations of Cd and Pb can cause aquatic life impairment in surface waters. The need to evaluate water quality at concentrations below reporting limits necessitated using estimated concentration values for analysis. Test America Laboratories, Inc. estimated and reported Cd and Pb concentrations down to the detection limit of 0.06 µg/L and 0.045 µg/L, respectively. Test America Laboratories, Inc. participates in National Environmental Laboratory Accreditation Program (http://www.nelac-institute.org/) requirements for all tested characteristics.

2.2.3.1.3 Canal Seepage Testing in the UARB Study Region

During the summers of 2009 and 2010, multiple tests were performed to estimate seepage loss rates in the Riverside Allen, Cottonwood Maxwell, and Salida canals. During each test, multiple measurements were made for each reach, and measurements were made over multiple reaches to evaluate seepage variability in time and space. Repeated tests also were used to discern the uncertainty in the results. Diurnal flow variations, gate in-take and off-take adjustments, and barometric pressure shifts among other factors can contribute to the uncertainty.

Determining canal seepage included site selection, test setup, collection of measurements, and data processing. Site selection and test setup involved map studies, reconnaissance, surveying, coordination with canal owners and stakeholders, selection of measurements sites, and placement of equipment. Collection of measurements involved obtaining multiple flow rate measurements along the reaches and documenting field conditions such as the opening and closing of diversion off-takes along the ditch and changes in stage. Data processing is discussed in Section 2.3.1.2.

Field surveying of the canal included photographing the canal in detail, measuring the canal length, and determining the locations of any relevant features. Features noted included gates, off-takes, leaks, inflows, outflows, stream crossings, structures, linings, and vegetation. Approximately every 0.2-mi, the cross section was surveyed at a representative location. This survey included the current surface water level along with canal bed and bank elevations up to 0.2 to 0.5 ft above the current water level. These measurements were collected to allow determination of the canal storage, wetted perimeter, and top width for different stage levels. At 0.5-mi intervals, a temporary stilling well (made of 2-in. slotted PVC) was driven into the bed and a pressure transducer was mounted inside. The transducer was the *Onset HOBO U20 Water Level Data Logger™*. The transducers recorded the water level every 1 min prior to and during the test. An additional pressure transducer measured barometric pressure near the mid-reach cross-section for stage measurement corrections.

Discharge measurements were collected at the upstream, mid-reach, and downstream cross-sections. These cross-sections were selected based on access and hydraulic considerations. A relatively straight and uniform flow approach with a well-defined cross section and a stable bed and stable banks were required to maximize flow measurement accuracy. In many cases, clearing debris, cutting vegetation, and clearing cobbles were necessary to produce adequate hydraulic conditions. Some cross sections required construction of a downstream rock weir to create sufficient backwater depths (at least 1 ft) for measurement. For each cross-section, a tape was used to measure position on the cross-section, a staff gage was used to measure stage, and the temporary stilling well with pressure transducer was installed.

Prior to testing, if available, data from pressure transducers at the upstream and downstream ends during the preceding days were analyzed to determine if a particular time of day was more suited for testing. Less variability in water level would reduce the storage changes in the reach and thereby reduce uncertainty. Immediately before collecting discharge measurements, the data were again analyzed to determine if a pulse of flow was moving into or out of the reach, which would indicate excessive storage change and poor timing of the test. Inflows along the reach from precipitation, drainages, and creeks were avoided through appropriate reach selection and by not testing during or immediately after storm events. Diversion outflows were controlled by coordinating with the canal supervisor to insure closure of gates prior to and during testing. For the day of the test, each canal was inspected for possible unanticipated inflows and outflows, which were measured or estimated and recorded.

Discharge was measured using the ADV (Figure 2.12) and the procedures described in Section 2.2.1.1. However, to reduce the time required for discharge measurement, the 4 to 8-ft wide cross-section was subdivided into only 10 to 20 subsections (rather than the 25 to 30 subsections used for streams). Long measurement times increase the risk that flow and stage will change during the test. To further reduce the measurement times, two teams simultaneously performed discharge measurements for the reach. Discharge was measured from upstream to downstream along the reach to better align with any pulse of flow moving downstream.

Figure 2.12: Discharge measurements in the Cottonwood Maxwell Ditch in August 2010.

2.2.3.2 Groundwater Measurements in the UARB Study Region

In early July 2009, the completed groundwater monitoring wells were visited for collection of initial measurements and installation of monitoring devices. The wells were measured for depth to the water table (from the top of the casing), depth to the bottom of the well (from the top of the casing), and distance from the top of the casing to the ground surface. In addition, a pressure transducer was suspended under water and near the bottom of the well, and it was set to record absolute pressure and temperature at 1-hour intervals. The transducer model used was the *Onset HOBO U20 Water Level Data Logger™*, which can measure water depths up to 100 ft. To distinguish water and atmospheric pressure, seven pressure transducers were deployed throughout the study region to measure barometric pressure. These transducers were suspended above the water table in wells that were spread throughout the study region. The selected wells were: 490804-01, 500822-02, 510808-01, 157824-01, 147925-01, 137925-01, and 127927-01.

2.2.3.2.1 In-Situ Monitoring of Groundwater in the UARB Study Region

Routine data collection at each well included down-hole in-situ measurements of EC, pH, DO, ORP, and *T* with the YSI multiprobe. The multiprobe was lowered into the well to the midpoint of the water column and allowed a minimum of 6 minutes, but sometimes more than 15 minutes, for the measurements to stabilize, with data recorded at three-minute intervals until variations of values were within tolerances. To determine water column height and check transducer-measured water table levels, a manual measurement of the water table was taken using a portable electronic water level meter, commonly called an electric tape. Finally, during each visit, the data loggers for water level and barometric pressure (if present) were downloaded for analysis. Multiprobe calibration and maintenance practices were the same as those used for surface water monitoring (Section 2.2.3.1.1).

2.2.3.2.2 Groundwater Quality Sampling in the UARB Study Region

Water samples were extracted from the monitoring wells using a *QED Sample Pro Portable Micro Purge Pump^{TM}* and low-flow sampling techniques from Puls and Barcelona (1996). Major equipment used in the sampling process is displayed in Figure 2.13. The pump cyclically forces compressed CO_2 to one side of a Teflon bladder, which forces water on the other side of the bladder to the surface. The water and gas tubes were made of 0.25-in. virgin polyethylene. The pump was positioned at the midpoint of the water column in the well. The pump was adjusted to a pumping rate between 200 and 300 mL/min, as measured in the water outlet tube at the surface. An electric tape was deployed 8 to 12 in below the water table and used to ensure that the pumping rate did not exceed the groundwater discharge rate into the well. Each water sample was taken at the outlet of the discharge tube through a 0.45-µm filter. The sampling procedures for quality control (blanks, duplicates, chain of custody, shipping, and laboratory methods) followed the same protocol as described for surface-water sampling in Section

2.2.3.1.2.

Figure 2.13: (Left) Groundwater sampling equipment: (clockwise, beginning lower left) electric tape and drawdown meter; pump tubing; bladder pump, sample bottles, large and small water filters, and filter attachment tube; YSI multiprobe, YSI handpad, and cable; peristaltic surface water pump; and groundwater power pack for bladder pump operation. (Right) Close-up of disassembled bladder pump with Teflon bladder.

During sampling, multiprobe measurements were taken in a flow-through cell at the ground surface in lieu of suspending the probe in the water column (as described for the monthly monitoring). Multiprobe measurements were taken at 3-minute intervals. At least two volumes of the flow-through cell were evacuated within each interval. Water samples were collected after at least three intervals were recorded and values had stabilized in the flow-through cell to: +/- 0.1 for pH, +/- 3% for EC, +/- 10 mV for ORP, and +/- 10% for DO (Puls and Barcelona 1996). Stabilization of *T* often was not possible and sometimes was biased from the true down-hole *T* value. This bias was due to exposure of the sampling tubes to sun or cold as the water was pumped from the well to the flow-through cell.

Bladder pump maintenance consisted of inspection and replacement of seals, screens, bladders, O-rings, and ball valves as needed prior to each sampling trip. The pump and flow-through cell were decontaminated prior to each well's sampling to avoid cross-contamination between wells. Decontamination involved dismantling the equipment into its components, pre-rinsing to remove visible dirt or debris, and then washing with a three-bucket (5-gallon) assembly line (Figure 2.14). This assembly line consisted of a bucket of phosphate-free detergent in tap water, a first rinse in a bucket of distilled water, and a second rinse in another bucket of distilled water, all prepared at the beginning of each day. For each bucket, pump cleaning involved submerging each component a minimum of three times and filling and clearing the bladder with each submergence.

To avoid cross-contamination, a different set of plastic tubing (i.e. water and gas tubes) was designated for each well. Prior to sampling, the designated tubing was decontaminated using a peristaltic pump to force a sequence of four solutions through the tubes following the same procedure used to clean surface water sampling tubes as described in Section 2.2.3.1.2.

Figure 2.14: Cleaning the *QED Sample Pro* bladder pump.

2.2.3.2.3 Slug Tests for Hydraulic Conductivity in the UARB Study Region

Slug testing was performed in January 2010 on 11 monitoring wells and again in July 2010 on all 17 wells in the monitoring network. The objective of slug testing was to provide a rough estimate of the hydraulic conductivity of the alluvial/outwash aquifer in the vicinity of each well. Hydraulic conductivity is a property of the aquifer that describes the ease with which water can move through the pore spaces (Schwartz and Zhang 2003). Estimating hydraulic conductivity is important for gaining an understanding of the movement of water between the alluvial/outwash aquifer and surface waters. Testing during the relative extremes in the groundwater cycle allowed hydraulic conductivity to be estimated under variable water table elevation levels.

A slug test involves creating a nearly instantaneous change in water table level through evacuation or addition of a volume (slug) of water to the aquifer via a well (ASTM 2008). By monitoring the subsequent recovery of the water table to its steady-state level, the near-well aquifer properties can be estimated. Figure 2.15 depicts an injection method in which a solid slug is lowered below the water table in a well, causing the water table to rise. A pressure transducer is shown below the slug influence area to measure the changes in the water level. After the water level recovers to its steady state water table elevation with the slug still in the water column, another slug test can be performed using the withdrawal method. By removing the solid slug, a drop in the water level occurs, and the aquifer will again recover to the steady-state water table level.

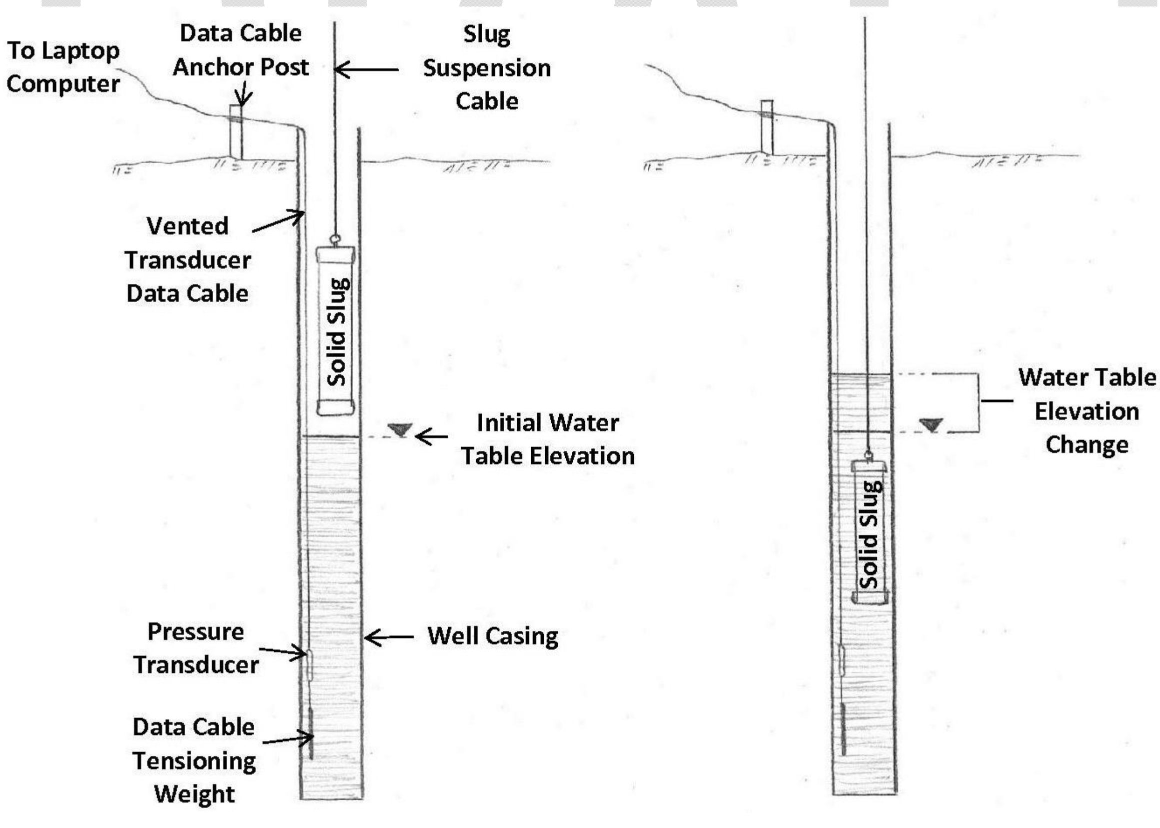


Figure 2.15: General schematic of an injection slug test, before (left) and immediately after (right) injection.

Slug tests have several advantages over aquifer tests. They are cost effective, do not contaminate the monitoring well through injection of non-native water, are repeatable at multiple wells, and are easy to execute. Slug tests also have disadvantages. Estimates of the hydraulic conductivity from slug tests describe the aquifer only inches to feet from the well. Given the heterogeneous nature of most aquifers, hydraulic conductivity estimates from slug tests and aquifer tests (which test properties over larger regions) can differ by more than order of magnitude.

The most common slug test method uses a bailer (Figure 2.16), a hollow polyethylene tube used to pull a volume of water from the well causing a reduction in water level. In this study, a separate bailer was used for each monitoring well to avoid cross-contamination. In addition, solid slugs of 4 and 6-ft lengths were constructed to achieve variable displacement volumes for both injection and withdrawal techniques (Figure 2.16 and Table 2.4). Solid slugs were PVC pipes filled with sand and sealed at both ends. The solid slugs were decontaminated between tests with a rinse of distilled water. Different approaches and displacement volumes were used to explore the sensitivity of the hydraulic conductivity estimates to the testing procedures.

Table 2.4: Displacement device characteristics for slug tests.

	Diameter (in.)	*Equivalent volume (ft^3)*	*Equivalent water level change in 2" well (in.)*	*(ft)*	*Method*
6-ft solid slug	1.25	0.057	31.20	2.60	Injection or Withdrawal
4-ft solid slug	1.25	0.039	21.70	1.81	Injection or Withdrawal
3-ft bailer (full)	1.5	0.040	21.92	1.83	Withdrawal

Both the well cuttings and the small changes in the water table levels that occurred during well development suggested that the hydraulic conductivity would be high and that the water levels would quickly recover during slug tests. In highly transmissive aquifers, the recovery rate of the water level in the well can be so rapid that slug tests have significant variability in early-time data, leading to difficulty in interpreting results. Estimation of aquifer storage properties in slug tests also are inaccurate because of affects from wellbore storage and well skin changes due to the borehole construction (Halford and Kuniasnsky 2002). For formations with high hydraulic conductivity, slug tests should be initiated rapidly and a series of tests should be performed at each well using a range of initial displacements (Butler 2003). Analytical solutions for calculating hydraulic conductivity from an analysis of the water level recovery assume an instantaneous change in water level. Rapid initiation is best achieved with a pneumatic (air) displacement technique, which was not possible in this study because the casings were screened above the water table. This configuration would allow air to escape through the screening and into the vadose zone above the water table. Thus, slug testing efforts were focused on achieving smooth yet quick insertion and withdrawal of three slug sizes with repeated performance of tests for each well.

Figure 2.16: (Left) Ready for a solid slug injection test at well 127927-01 in July 2010. (Right) Various slug test devices used: (from left to right) 3-ft bailer, 4-ft solid slug, and 6-ft solid slug.

An *In-Situ Level TROLL 700*^{TM} pressure transducer was selected for use in the slug tests because it has the capability to measure the water level at up to four times per second, is vented for automatic atmospheric correction, and has a logarithmic mode, which samples at a maximum of 4 times per second for the first 6 seconds then at a logarithmically-decreasing rate thereafter. Figure 2.17 shows some of the equipment used in performance of the slug tests.

The slug testing procedure is illustrated by the schematic in Figure 2.15. To limit cross-contamination between wells, all equipment was rinsed with distilled water before insertion into the well. Each well was prepared by measuring the initial static water-table level and the depth to the bottom of the well casing. The set-up of the slugs involved measuring the suspension cable and marking the depth for lowering the slug to just below the water table as well as the depth at which the slug would be just above the static water-table level. The pressure transducer set-up involved placing the device in the water column and securing the control cable to a ground stake to ensure a constant suspension depth. For the July tests, a weight (an iron bar) was suspended at the end of the transducer cable, below the transducer. The weight helps reduce the movement of the transducer when the slug is inserted or withdrawn from the well, and it helps prevent the cable from shrinking while in contact with the colder water in the well. For the July tests, the pressure transducer was also placed as close as possible to the static water-table level to reduce water-column acceleration effects (Butler 2003).

Figure 2.17: Slug test equipment and well monitoring accessories (from left, clockwise to center): 6-ft solid slug and suspension cable reel, 3-ft bailer, hammer, clamp, stakes, well cover, socket wrench, vented data logger cable (blue), Level Troll® 700 data logger (silver w/ black tip), black iron weight, transducer suspension string (pink), transducer, j-plug cap, steel tape, and electric water-level indicator.

Prior to insertion or withdrawal of a slug, a confirmation of a stable water table level was made via the deployed pressure transducer (via a laptop). The pressure transducer began recording approximately 3 sec prior to insertion or withdrawal of a slug. The slug was lowered or withdrawn in a smooth but rapid motion that avoided splashing. Water level recovery was monitored on the computer until it recovered to within about 5% of the static level. The technique was repeated for at least 6 insertions or withdrawals with successful measurements. Field checks included comparing the expected water level displacement with measured displacement, confirmation of a full bailer withdrawal, and insuring that no entanglement or movement occurred with the pressure transducer or control cables.

2.3 Data Analysis and Results for the UARB Study Region

This chapter summarizes the main observations gathered over the study period and the corresponding data analysis. The discussion of the surface water compares the flows during the study period to the long-term records to provide some context. The flow records also are examined to evaluate possible long-term trends. Mass balance calculations for flows through the study region enable an analysis of the contributions of measured sources and other unmeasured sources. Analysis of canal seepage tests provides insight into the role of irrigation as a source of recharge to the alluvial/outwash aquifers.

Groundwater monitoring results include a discussion of several monitoring-well water table depth, D_{wt}, and T plots that explain some of the temporal and spatial variability in the alluvial/outwash aquifer and factors that influence it. An analysis of the monitoring well network as a whole allows for broader insight into the changes in water table level during the study period and the relationship to irrigation recharge sources. The slug test analysis provides a general characterization of the alluvial/outwash aquifer's hydraulic conductivity.

The water quality data allow statistical evaluations of basic characteristics and concentrations of the tested constituents. The analysis and discussion of results identifies areas of interest for possible future monitoring. TDS, as a basic indicator of overall water quality, is evaluated in detail for relationships to EC and for the dynamics of TDS in the surface water system. Comparison of TDS concentrations in the surface and groundwater in light of the mass balance analysis provides further evidence supporting the nature of aquifer-stream connectivity.

2.3.1 Surface Water Quantity in the UARB Study Region

Discharge at sites without permanent gages was determined from measurements when accessible and safe, and at gaged sites, by means of agency database records coincident to in-situ measurements. During the period of June 2009 through November 2011, 8 to 10 monthly discharge measurements were made, totaling 202 during the study period. The expansive agency datasets available for gaged sites were utilized for long-term averaging and study period flow comparisons; analysis of thousands of data points allowed determination of flow-contributing sources, long-term mean daily point flows, river dynamics, and seasonal variability.

2.3.1.1 Surface Water Flow-Rates in the UARB Study Region

A statistical summary of Arkansas River tributary flow measurements is presented in Table 2.5. The table represents results for all surface water monitoring locations with five or more flow measurements. The highest mean flow was recorded on the South Arkansas River near Salida. The lowest flows were recorded on Four Mile Creek. Discharges less than about 1 ft^3/s were estimated by multiplying the measured cross-sectional area by the estimated flow velocity where the estimated velocity was determined by timing a floating object, usually a stick or pinecone, over a 10-foot distance several times and calculating an average speed. The largest measured flow (228.2 ft^3/s) in the tributaries was recorded at the upstream monitoring station on Chalk Creek on June 4, 2011.

Table 2.5: Flow statistics for Arkansas River tributary monitoring stations with five or more flow measurements.

Site Location	*Designation*	*Number of measurements*	*Minimum Measured Flow* (ft^3/s)	*Maximum Measured Flow* (ft^3/s)	*Mean Measured Flow* (ft^3/s)
Four Mile Creek - Downstream	*4MILED*	20	0.1	13.3	2.3
Browns Creek - Downstream	*BRNCKD*	23	1.0	13.7	4.4
Browns Creek - Upstream	*BRNCKU*	16	2.4	25.7	9.0
Chalk Creek - Upstream	*CHCKU*	24	9.3	228.2	51.7
Clear Creek - Upstream	*CLRCKU*	17	6.6	139.3	32.6
Cottonwood Creek - Hotsprings	*COCRHSCO*	5	13.8	50.0	25.9
Cottonwood Creek - Upstream	*MCOTU*	19	5.9	103.1	23.4
North Cottonwood Creek - Downstream	*NCOTD*	18	0.2	60.7	11.8
North Fork South Arkansas River	*NFSOAKCO*	5	5.5	25.3	16.1
South Arkansas River - Upstream	*SARKU*	19	4.0	146.1	28.3
South Cottonwood Creek - Upstream	*SCOTU*	21	0.4	81.2	18.6
South Arkansas River - Downstream	*SOAKTECO*	5	13.2	54.7	36.0

Figure 2.18 shows the daily average flow rate at four gage sites along the Arkansas River normalized by dividing the average flow rate on a given day during the study period by the long-term average flow rates for the same date within the year. A value of one suggests a water year in which the daily flow is on average close to the long-term average value. The Wellsville gage was not in the monitoring network but forms a convenient downstream boundary for the river study reach. Long-term USGS flow data are available for the Wellsville gage, and it is located only 2.8 mi downstream from the South Arkansas River confluence. Using the Wellsville gage data as the downstream boundary enables the inclusion of the South Arkansas River discharge in a mass balance analysis of the system. The long-term average flow rate for each gage was calculated using the preceding 20 to 25 years, depending on the available records. The plot shows a noteworthy consistency among all four sites in the flow patterns during the study period. The averages of the normalized flow rates during the study period for the Granite, Nathrop, Salida, and Wellsville gages are 1.12, 1.02, 1.03, and 1.01 respectively. These values suggest that, during the study period as a whole, the flows at these sites were close to or slightly above the long-term average conditions. The plot illustrates above-average flows in the last quarter of 2009, during the snowmelt runoff period in late May and June 2010, and late in the study period. Below average flows generally are

indicated early in the study period, in the first quarter of 2010, around April to early May 2010, and again in April to early May 2011.

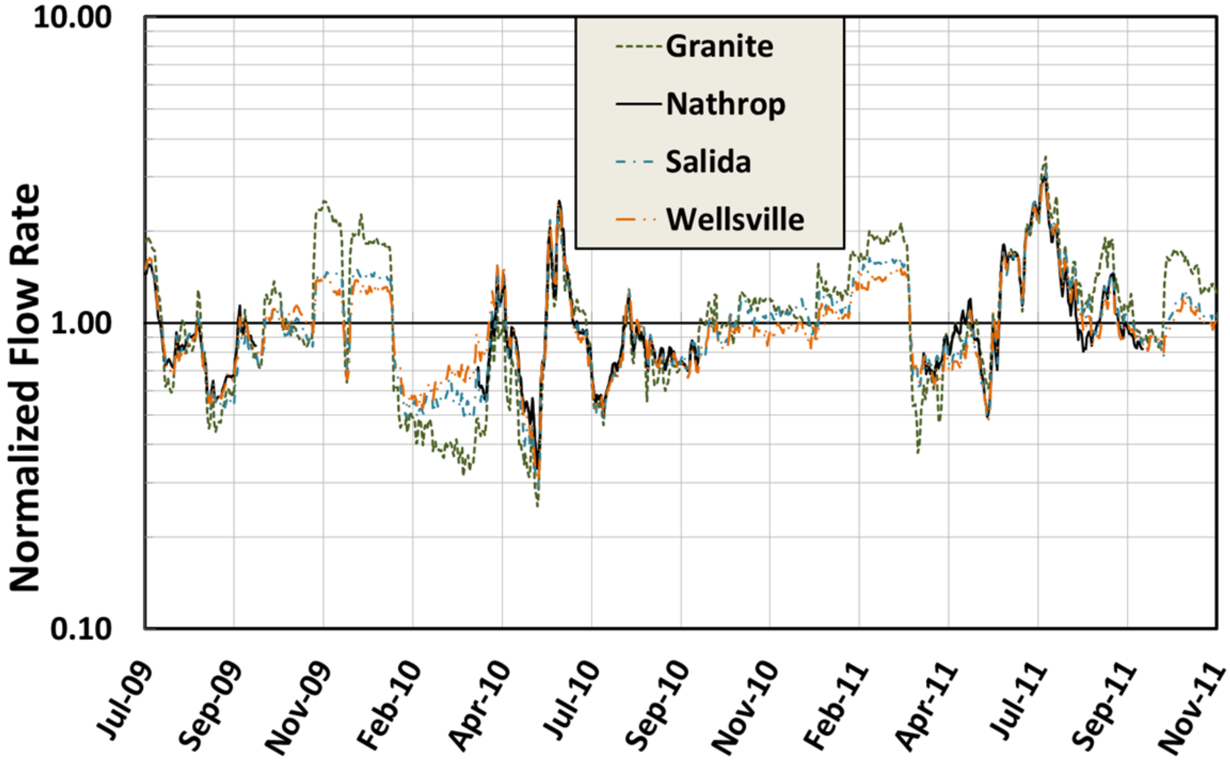


Figure 2.18: Normalized daily average flow rate at four Arkansas River gages (from north to south) in or near the UARB study region during the study period.

Figure 2.19 shows a similar plot for four tributary gages near their confluences with the Arkansas River. Overall, the tributaries exhibit much more variability in their normalized flows than the Arkansas River. The tributary flows range from around 2% to 1000% of normal, while the Arkansas River sites range from around 30% to 200% of normal. Both plots reflect a notable spike during the 2010 snowpack runoff, which was widely known at the time for its flashy peak. The period with below-average flow in the first quarter of 2010 is not consistently present in the tributary plots. The periods with below-average flow from April to early May 2010 and 2011 are present in both figures, but they are much less pronounced for the tributaries.

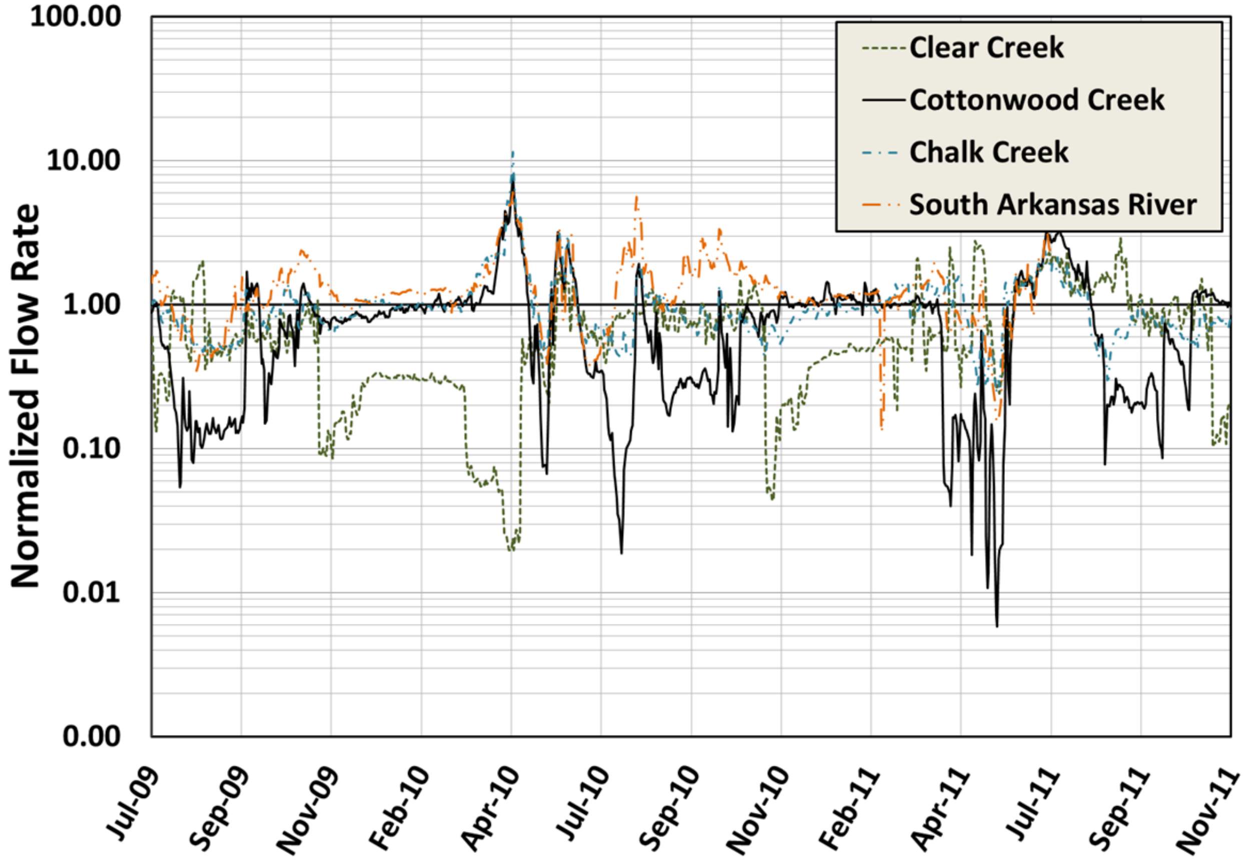


Figure 2.19: Normalized daily mean flow-rate at four tributary gages (from north to south) in the UARB study region during the study period.

The averages of the normalized flow rates during the study period for Clear Creek, Cottonwood Creek, Chalk Creek, and the South Arkansas River are 0.72, 0.86, 1.03, and 1.35, respectively. The Clear Creek gage is just downstream of Clear Creek Reservoir and reflects controlled releases from the reservoir. Abrupt jumps on November 15 and April 15 in the Clear Creek plot suggest significant adjustments in the reservoir releases on those dates compared with long-term operations. The low average value for Clear Creek might suggest that Clear Creek Reservoir was in a period of greater storage gain compared to its average operation. The large value for the average normalized flow in the South Arkansas River occurs in part due to high flows during October 2009, July 2010, and September through November 2010. The gage at the South Arkansas River confluence provided only provisional data due to long-term impairment of the gage. Thus, these observations are less reliable. In addition, the provisional data are only available for 13 years (water year 1996 to 2009).

Cottonwood Creek and Chalk Creek had nearly normal flows during the study period. Both plots track more closely to the long-term average during the non-irrigation season and display more variability during the irrigation season. Greater relative variability in the Cottonwood Creek plot during the irrigation season could be due to stronger anthropogenic influences. Cottonwood Creek runs through the town of Buena Vista, contains multiple upstream reservoirs, and, according to the records of Water District 11 found at the Chaffee County Courthouse, is subject to 63 adjudicated water rights totaling over 213 ft^3/s. In comparison, Chalk Creek has only 29 adjudicated rights totaling 150 ft^3/s. The average flow at the Cottonwood Creek and Chalk Creek gages during the irrigation season are 36 and 61 ft^3/s, respectively. Long-term averaged maximum daily flows during the irrigation season are 140 and 219 ft^3/s, respectively.

Figure 2.20 facilitates examination of whether long-term trends are occurring in the discharge at selected gages. The Nathrop and Clear Creek gages are not shown because of seasonal-only operation and highly controlled reservoir release flows, respectively. The South Arkansas River also is excluded because of shorter-term data (1996-2008) and provisional data status. To create the plot, the ratio of the daily mean flow to the average daily mean flow over the period of 1983 to 2008 was calculated for every day from 1983 to 2008. The average of all the daily ratio values in each water year (October 1 – September 30) is then plotted in the figure. Prolonged periods of above and below average flow are observed for all five gages, and these variations overwhelm any trend. Cottonwood Creek's variation from average is larger than the other gages, with higher peaks and lower valleys in the plot (note that data are unavailable for this gage from 1988 to 1992).

Seasonal flow rates also were analyzed to understand the contributions from tributaries to the main stem of the Arkansas River as well as potential gains and losses from other sources including groundwater and irrigation diversions. The irrigation season in the UARB typically runs from around April 15 to October 15 (D. Kelly, CDWR Deputy Water Commissioner, personal communication, January 5, 2011). Each year of the long-term gage records was divided into the irrigation season and the remainder of the year, which is termed the non-irrigation season.

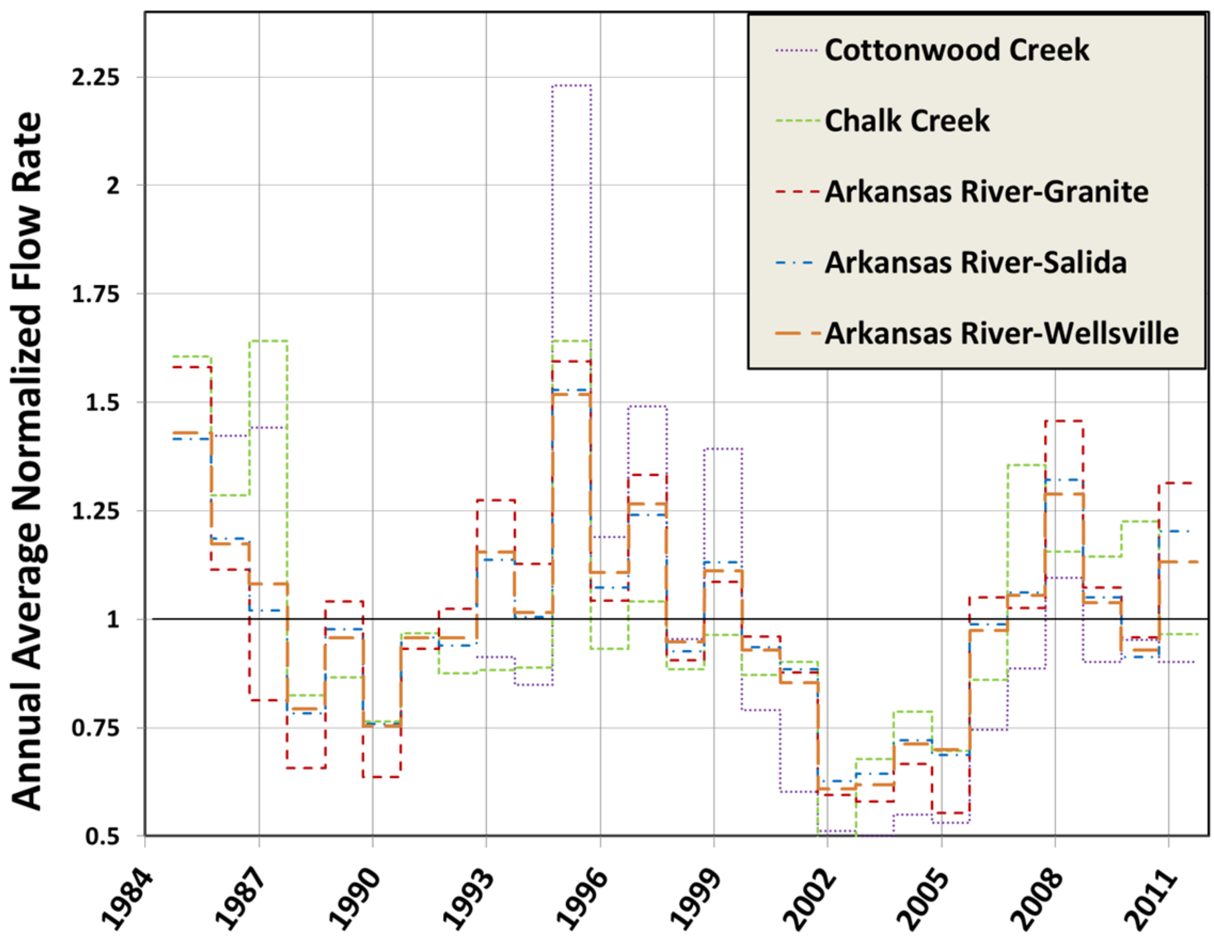


Figure 2.20: Water year (Oct 1 – Sept 30) average of normalized daily mean flow rates at selected gages in or near the UARB study region.

In analyzing long-term data for the irrigation season, it was found that the daily discharge in the main stem of the Arkansas River increases an average of 81% (384 ft^3/s) along the reach between Granite and Wellsville. Gaged inflows from Clear Creek, Cottonwood Creek, Chalk Creek, and the South Arkansas River supply 264 ft^3/s of this increase. Based on the eleven discharge measurements taken during the irrigation seasons for 2009, 2010, and 2011, Fourmile Creek and Browns Creek contribute only about 10 ft^3/s to the flow increase. During the non-irrigation season, the Arkansas River increases by 129% (222 ft^3/s), with a contribution of about 88 ft^3/s from the four major tributaries and about 9 ft^3/s from Fourmile and Browns Creeks.

By removing the contribution from the gaged tributaries, the daily average river flow increase from Granite to Wellsville is 39% and 60% during irrigation and non-irrigation seasons, respectively. This net increase encompasses the difference between unmeasured inflows like groundwater discharge, irrigation return flows in surface drains, other unmeasured tributaries, overland flow, and direct precipitation; unaccounted-for outflows like recharge to aquifers, irrigation withdrawals, evaporation, and riparian transpiration; and changes in stored volume within the river reach. When the hydraulic gradient drives flow out of the river to recharge the groundwater aquifer, such interaction would carry a negative value in the mass balance analysis. This condition could occur due to seasonally low water table levels or localized drawdowns from high-rate pumping wells.

Focusing on the study period, the Arkansas River flow increased from Granite to Wellsville by 83% (389 ft^3/s) and 122% (203 ft^3/s) during the irrigation and non-irrigation seasons, respectively. Tributary contributions of 253 ft^3/s and 89 ft^3/s were estimated for the irrigation and non-irrigation seasons, respectively. Other net sources contributed 136 ft^3/s and 114 ft^3/s for irrigation and non-irrigation seasons, respectively. Table 4.2 shows these increases both in terms of flow rates and percent increases. The values indicate a similarity between the long-term gage dataset and the shorter-term dataset for the irrigation and non-irrigation seasons. These statistics suggest that the net contributions from unaccounted-for flows are relatively constant between the seasons but are proportionally much more significant during the non-irrigation season when the total river flow and the increase over the reach are smaller.

Table 2.6: Seasonal analysis of average daily Arkansas River discharge increases and relative percent increase from Granite to Wellsville, and the discharge increase contributing sources with percent of contribution.

	Irrigation Season				*Non-Irrigation Season*			
	Increase in Long-Term Dataset		*Increase in Study Period Dataset*		*Increase in Long-Term Dataset*		*Increase in Study Period Dataset*	
	(ft^3/s)	*(%)*	*(ft^3/s)*	*(%)*	*(ft^3/s)*	*(%)*	*(ft^3/s)*	*(%)*
Granite to Wellsville Flow Increase	384	81%	389	83%	222	129%	203	122%
Tributary Contribution	264	61%	253	60%	88	40%	89	45%
Other Net Contribution	120	39%	136	40%	134	60%	114	55%

Figure 2.21 is a plot of the net contributions from unaccounted-for flows based on a daily mass balance analysis for the study period and the long-term gage data. These net contributions during the study period are quite variable and have a mean value of 126 ft^3/s. No early summer spike occurs in the long-term dataset. However, noticeable peaks occur during the early summer for 2009, 2010, and 2011. The peak is particularly noticeable in 2010 when dust from desert windstorms coated the mountain snowpack (Rappold 2010). This dusting helped speed up the snowmelt by reducing the snow's reflectance of solar energy (Laustesen et al. 2010). One might expect that rapid snowmelt would be more visible in the gaged tributaries than the unaccounted-for sources. A spike is seen here due to differences in the timing of the flows in the tributaries and main stem. The contribution from gaged tributaries begins decreasing while the discharge in the main stem remains elevated, which produces the spike in Figure 2.21. Such inconsistency can occur if the snowmelt flows are highly flashy.

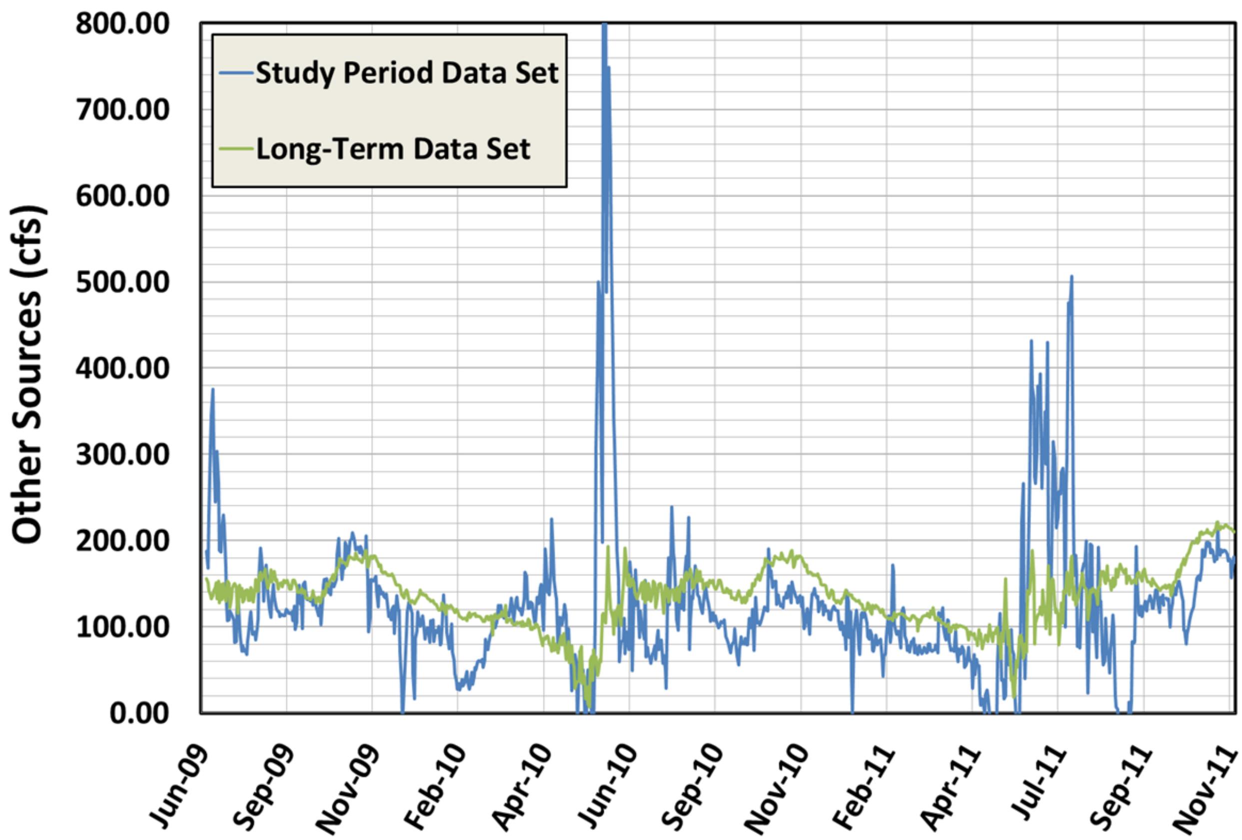


Figure 2.21: Quantification of net flow increase from unaccounted-for flows from Granite to Wellsville.

The long-term plot line in Figure 2.21 shows unaccounted-for source contributions peaking near 200 ft^3/s around June, which is coincident with the snowmelt runoff period. The minimum contribution is only a month prior (May), which is just before the snowmelt. The minimum value might occur at this time because river flow is being lost to the aquifers. The aquifers are at their lowest levels at this time and therefore most likely to have river inflow. Following the June peak, unaccounted-for net contributions are relatively stable through the summer and then rise to a secondary maximum level of around 190 ft^3/s that persists from October into November. This high period is followed by a relatively steady decline through the winter months. The lack of a significant peak in the unaccounted-for sources from snowmelt suggests that the gaged tributaries are the principal outlet for snowmelt in the study region in most years. Moreover, the presence of a relative stable contribution from June to November may be due primarily to groundwater flow contributions from consistent irrigation. This interpretation would suggest that 30 to 60 days following the start of irrigation season, around April 15, a consistent unaccounted-for net contribution dominated by groundwater inflow is present and does not steadily decrease until 30 to 60 days following the end of the irrigation season, around October 15. An example illustrating this groundwater-dominated contribution is demonstrated in the reach from Nathrop to Salida, which lacks any perennial tributaries. During the irrigation season, several large irrigation diversions in this reach withdraw as much as 13% (102 ft^3/s) of the main stem flow; however, the net river reduction is only 3% (23 ft^3/s). In this 11-mi reach, a mean groundwater-dominated inflow would be approximately 80 ft^3/s.

2.3.1.2 Canal Seepage in the UARB Study Region

Seepage tests were performed on the Riverside Allen, Cottonwood Maxwell, and Salida canals. For each canal, an approximately 4-mi reach was subdivided into an upper and lower segment. Three tests were performed on the Riverside Allen Canal, and two tests were performed on the Cottonwood Maxwell and Salida canals. All tests were conducted during the summers of 2009 and 2010. During each test, multiple measurements of upstream and downstream cross-section discharge were collected.

The mass balance equation used in the analysis to determine the seepage loss rates in the canal reaches is presented as,

$$Q_s = Q_{us} - Q_{ds} + Q_i - Q_d - Q_E - \Delta S/\Delta t \quad (2.1)$$

Where

Q_s = Total seepage loss (ft^3/s),
Q_{us} = Canal inflow rate through the upstream cross section (ft^3/s),
Q_{ds} = Canal outflow rate through the downstream cross section (ft^3/s),
Q_i = Total rate of inflows along the canal reach (ft^3/s),
Q_d = Total rate of outflow diverted along the reach (ft^3/s),
Q_E = Total rate of evaporation from the water surface along the reach (ft^3/s), and
$\Delta S/\Delta t$ = Rate of change of stored water within the canal reach (ft^3/s).

Evaporation from the water surface was estimated using two methods: the Penman Combination Equation and regional pan evaporation rates (WRCC 2010). From both methods, evaporation from the water surface was calculated to be equivalent to about 0.05 ft^3/s during the test period, which is negligible for purposes of this analysis.

The rate of change in stored water in the canal reach during the test period was determined using stage data gathered from the pressure transducers along the reach and canal top width surveys conducted at the 0.2-mi interval cross-sections. For each 0.2-mi interval, the rate of change in stored water was calculated as the stage change times the average canal top width times the subject reach length divided by the duration of the test. Because this calculation is approximate, testing conditions are better for cases where negligible changes in stage occurred. Rate of storage change values ranged from 0.00 to 0.84 ft^3/s. Some stage changes were highly variable over time at different sections of the canal and resulted in inconclusive datasets, supporting the need for multiple discharge measurements for each test.

A summary of seepage losses in the test reaches of the ditches is presented in Table 2.7. The table represents results over the entire reach for the Riverside Allen Canal (4.1 mi) and the Cottonwood Maxwell Canal (3.6 mi), and the lower segment only on the Salida Canal (2 mi). The upper segment of the Salida Canal reach contained several diversion off-takes with poorly controlled flows during the test period, resulting in unreliable calculations. The number of discharge measurement sets used in the calculations is shown in the table and provides an indication of the relative certainty of the results.

Table 2.7: Canal seepage rate study summary results.

	Riverside Allen Canal			*Cottonwood Maxwell Canal*		*Salida Canal*	
	July '09	*June '10*	*August '10*	*May '10*	*August '10*	*June '10*	*August '10*
No. of measurements	1	2	2	3	2	3	1
ft^3/s per mile	0.28	0.67	0.61	1.26	0.67	0.44	0.8
ac-ft/day	2.2	5.3	5.7	9.1	4.8	1.7	3.1
ft/day	0.6	1.4	1.5	1.3	1.3	0.8	1.4
Percent	36%	43%	45%	31%	43%	9%	21%

The cross-section surveys also were used to determine the wetted perimeter, which was combined with the canal length to estimate the total wetted-perimeter area of the ditches. The wetted-perimeter area was then used to convert seepage rates into units that are less dependent on ditch size and flow rate. In particular, seepage can be calculated as ft/day. The average value for all canal seepage tests is 1.2 ft /day through the wetted perimeter area. Overall, seepage losses comprise a substantial portion of the total flow and have an average value of 0.7 ft^3/s per mi.

2.3.2 Groundwater Quantity in the UARB Study Region

2.3.2.1 Water Table Levels in the UARB Study Region

Based on the hourly measurements from all pressure transducers in the 17-well monitoring network, values of D_{wt} ranged from 0 to nearly 66 ft below ground surface. The overall average D_{wt} was 20.8 ft. Some wells showed high variability and clear seasonality while other wells exhibited relatively constant value of D_{wt} throughout the study period.

One goal of the study was to characterize the interaction of the alluvial/outwash aquifer and the surface water in the region. To some degree, this relationship can be characterized through an evaluation of D_{wt} in the alluvial/outwash aquifer through time. Figures 2.22, 2.23, and 2.24 plot the D_{wt} and water T through time for three example monitoring wells.

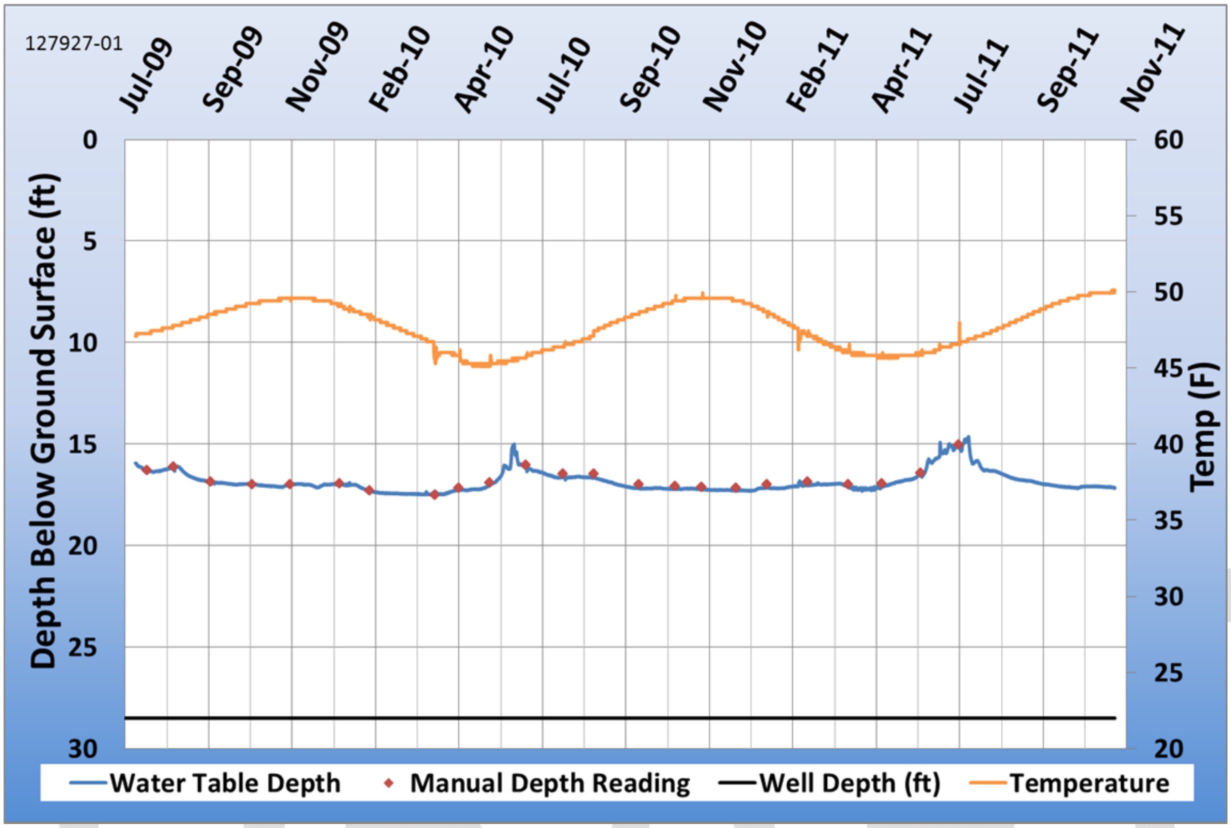


Figure 2.22. Records of D_{wt} and T for well 127927-01, located north of Buena Vista, near the Arkansas River and with minimal nearby irrigation activity.

Figure 2.22 shows a monitoring well (127927-01) with relatively constant D_{wt} and T values. The well is located within 500 ft of the Arkansas River in a horse pasture that receives limited application of irrigation water (see location in Figure 2.10). The generally stable water table with the small (approximately 2.5 ft) jump in June 2010, at the time of the snowpack run-off and annual Arkansas River peak flow, suggest some connection with the river main stem. The record of T exhibits a very smooth and predictable annual variation. Short-term variability in T occurring during late winter, as shown by the small fluctuations, was confirmed to coincide with snowfall events. The groundwater T peaks in the period around November and December, which is contrary to the river T behavior. At a nearby river gage in Granite, Treaches its maximum in August at around 59˚F and its minimum from mid-November to early March in the 32 ˚F to 37˚F range. Although an aquifer to river connection is apparent in the water table levels, the disparity in T suggests that residual warmth from the ground and other water sources dominates the groundwater T. The range of fluctuation in $T$is seen here is 4.8 ˚F, which is lower than the average range across all wells (6.2 ˚F). Additional regional T analysis is discussed in Section 2.3.3.1.

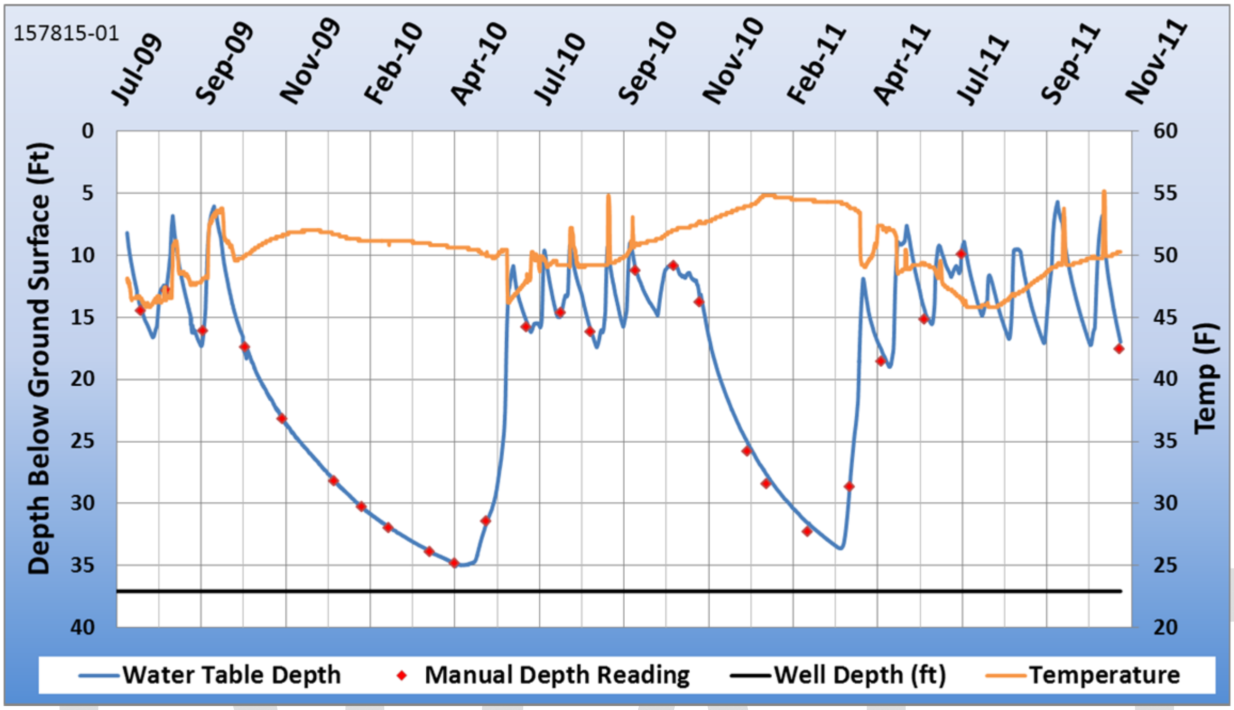


Figure 2.23. Records of D_{wt} and T for well 157815-01, located near Nathrop, down gradient of irrigation ditch and flood irrigation activities.

Figures 2.23 and 2.24 both illustrate cases with significant changes in D_{wt} and T during the study period. Water table levels show both an annual periodic trend, with a higher water table in summer and lower in winter, as well as some short-term fluctuations during the summer period. The application of irrigation water likely causes these short-term variations (based on personal communications with the owners of the surrounding property). Both monitoring wells are in pastures with no irrigation, but irrigated hay fields are located 100-200 ft upslope from the wells.

The monitoring well depicted in Figure 2.23 (157815-01, see location in Figure 2.10) is located 1500 ft south and 50 ft above the Chalk Creek flood plain and several miles west of the Arkansas River. The plot exhibits multiple distinct peaks in the water table level during the summer, reflecting the up-gradient flood irrigation practices. Groundwater T also changes with these irrigation cycles. After summer irrigation activities cease, water table levels steadily drop by almost 30 ft before the next year's irrigation begins. Values of T remain more constant during the winter season. A difference of approximately 4 ˚F from winter 2010 to 2011 may be indicative of differences in the insulating snow cover. The overall range in T values is relatively high (9.0 ˚F). The average range across all wells is 6.2 ˚F.

The D_{wt} and T data in Figure 2.24 are from a monitoring well (157824-01, see location in Figure 2.10) that is located approximately 1500 ft from the Arkansas River but directly down-slope from expansive flood-irrigated hay meadows. This plot shows a stable winter water table depth around 22 ft, which is likely due to its proximity to the river. During the irrigation season, the water table climbs and remains high until an abrupt decrease and subsequent increase occur in late summer. Based on personal communications, the landowner halted irrigation in late summer to allow the fields to dry and hay to be cut, then resumed irrigating as long as the water rights allowed. Values of T show abrupt fluctuations during the irrigation seasons and steady decreases during the non-irrigation periods. Some periodicity does appear to be present (with the irrigation season fluctuations superimposed). The overall range in temperature is 12.6 ˚F.

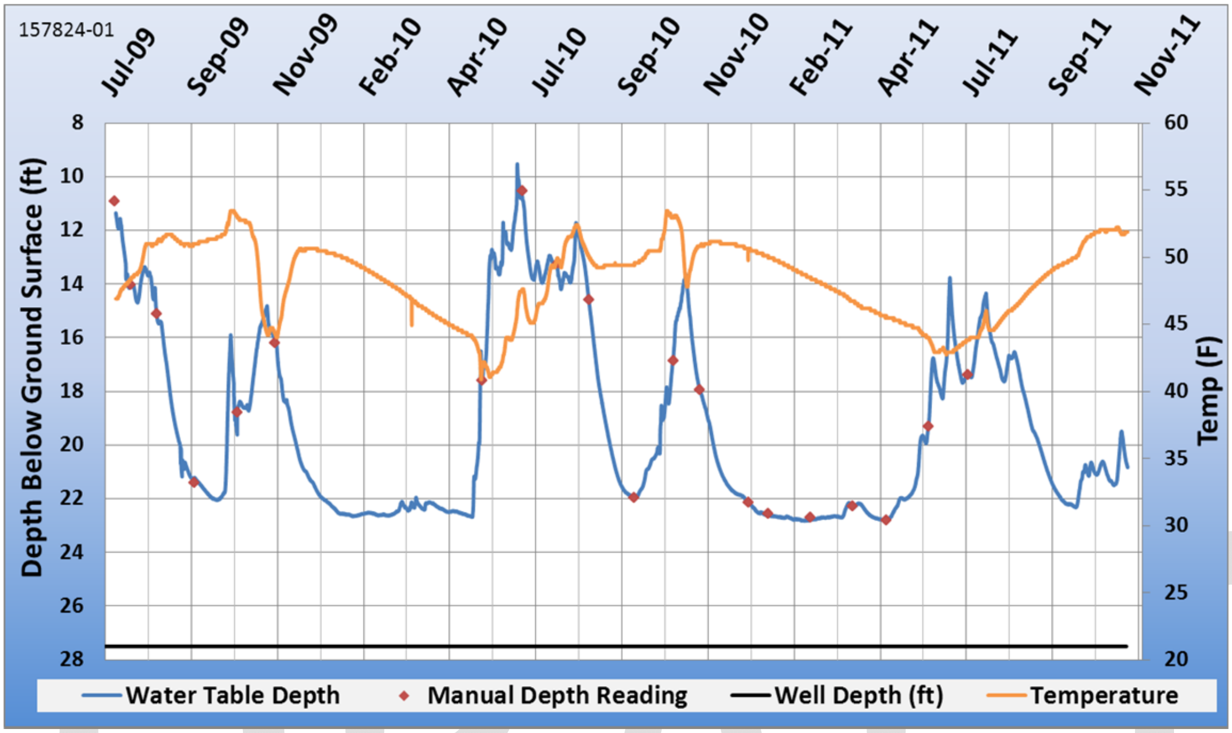


Figure 2.24. Records of D_{wt} and T for well 157824-01, located near Nathrop and close to the Arkansas River but down gradient of irrigation activities.

Overall, 10 of 17 monitoring wells show a clear influence of local irrigation activities, and 5 wells show water table levels that indicate possible connections with the Arkansas River or a nearby perennial tributary. One remaining well (500813-01) shows a gradually rising and falling water table with an 8 ft range in D_{wt} throughout the year. This well has the smallest range in temperature (0.4 ˚F) and is just down slope of the Salida Ditch. The well shows no conclusive evidence indicating an influence from the nearby canal and irrigated areas. The annual oscillation of D_{wt} and the relatively steady value of T may be due to a consistent gradual down-gradient movement of groundwater from the valley to the well. This interpretation is supported by the well's location, which is at the downstream end of the rift valley near the Arkansas River outlet point. The last well (500822-02) is surprisingly static throughout the year (a 3 ft range in water table depth) and shows no influence from a nearby irrigation canal (600 ft away) or the Arkansas River (approximately 1100 ft away). The area is extremely dry, and very little irrigation activity occurs in the immediate vicinity. At a nearby slope to the Arkansas River flood plain, however, many natural seeps flow all year and many more flow while the irrigation canal is flowing. The well's T value is also interesting because it has the highest average value and the second smallest range (0.9 ˚F). This well is in an area called Sand Park, which is near Salida, inside a large bend of the Arkansas River (called Big Bend). This well is also the deepest and may be connected to a confined or semi-confined aquifer with different hydrologic tendencies. An additional exceptional characteristic of this well is discussed in Section 2.3.3.2.2.

Figure 2.25 shows the deviation of each water table level from its average depth during the study period. Positive deviations in this plot indicate shallower D_{wt} (or higher water table elevations). Some wells show large variability, and others have stable water table levels. The average of all the deviations (solid black line) demonstrates how the water table throughout the monitoring region changes during the study period. Overall, the water table is consistently high during the summer months with some variability that is largely associated with irrigation activities. Around late October, the erratic variability changes to a smooth decrease in the water table level. In spring, the average shows a relatively abrupt increase from the winter minimum to the higher summer average.

The seasonal amplitude of the average water table level suggests that aquifer levels during the study period generally move within a range of 4 ft below to 3 or 4 ft above the mean. Figure 2.25 also depicts the average line of the ten irrigation-influenced wells. The seasonal amplitude of their average is almost double the overall well average, ranging from about 7 ft below to 7 ft above the mean. In contrast, the remaining seven wells show very little seasonality in their water table levels and appear to be dominated by influence from stable water sources such as nearby surface water.

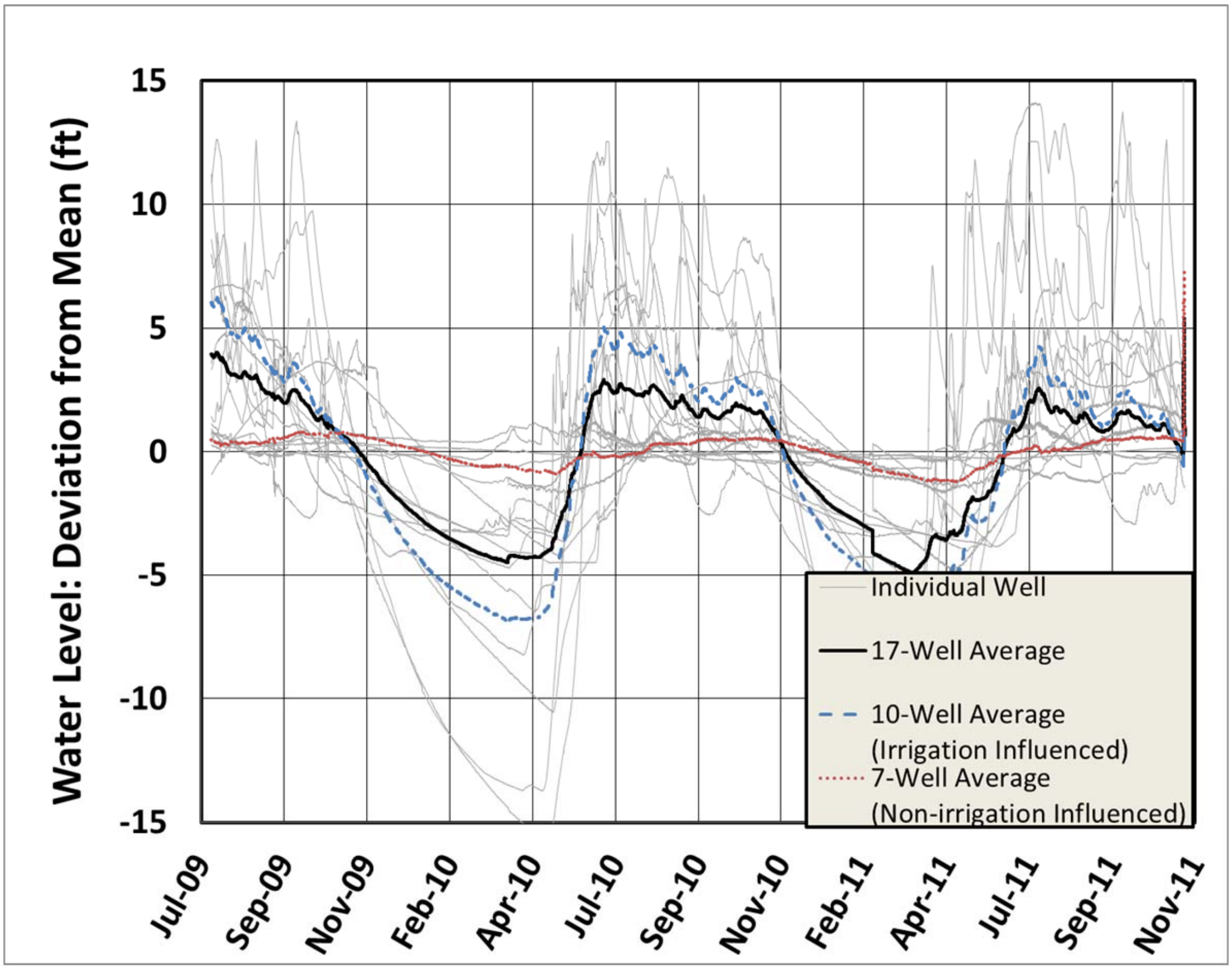


Figure 2.25: UARB study region monitoring well network water table level deviation from mean level through the study period.

Figure 2.26 shows the water table levels in each well when they are normalized by their extreme values. For each well, one on the vertical axis represents the highest recorded water table level and zero represents the lowest recorded water table level. A pattern similar to that noted for Figure 2.25 emerges.

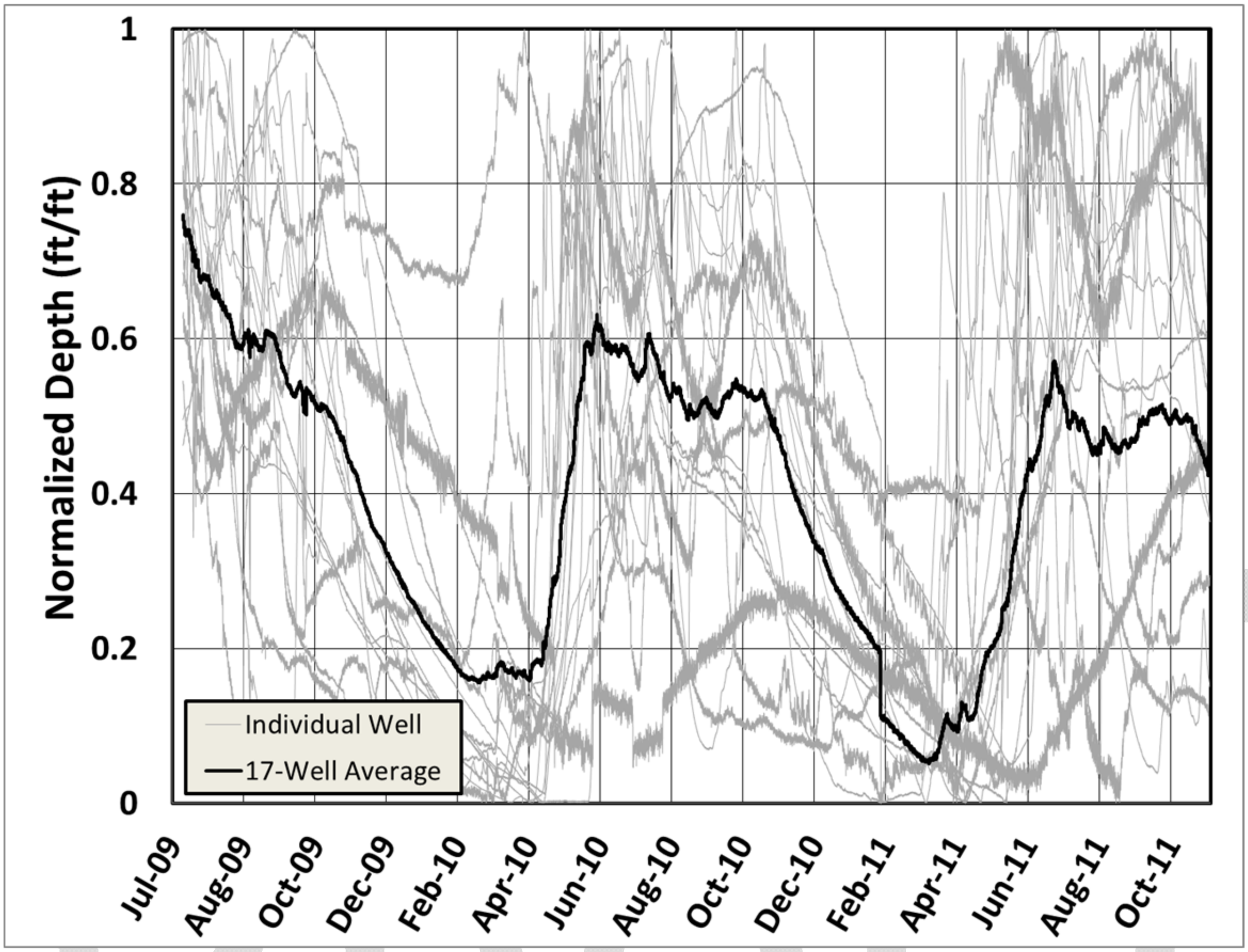


Figure 2.26: Normalized water table depths for all groundwater monitoring wells in the UARB study region and as an average.

2.3.2.2 Aquifer Hydraulic Conductivity in the UARB Study Region

Estimates of hydraulic conductivity in the alluvial/outwash aquifer materials were made through slug tests on the monitoring wells. A minimum of six, and often many more, slug tests were performed in each monitoring well during January and July 2010. In January, only 11 of 17 wells were tested due to winter inaccessibility and lack of suitable water column heights in some wells. All 17 wells were tested in July. Typically, three or four tests were successful for each well during both periods of testing. Measured displacement in the water level for the viable tests was 15% to 50% of the displacement calculated from the actual slug volume.

Figure 2.27 is a plot of the initial water table response during an injection-method slug test using a 6-ft solid slug. Upon slug insertion into the well, the water level rises quickly and subsequently recovers quickly to near steady state with a slight oscillation and finally an asymptotic approach back toward pre-test water table levels. The plot shows a 0.9-ft displacement from the steady-state water table conditions. This displacement is the equivalent of 35% of expected displacement calculated from the lab-measured slug volume. A 90% recovery to the pre-test water-level occurs about 2 s after slug insertion.

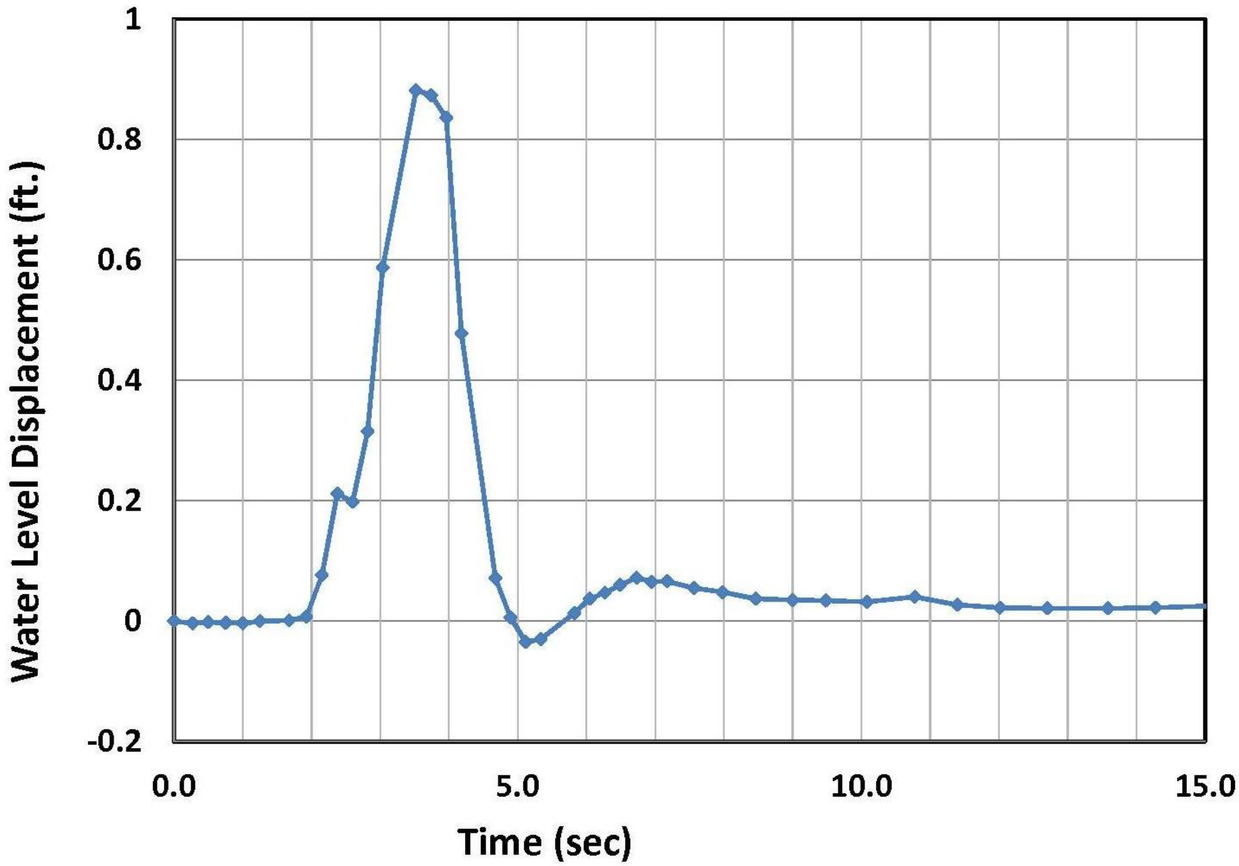


Figure 2.27: Slug test plot of the response of water level in a groundwater monitoring well in the UARB study region to a 6-ft solid slug injection.

Three analytical techniques were used to interpret the slug test data [(Butler and Garnett 2000), (Halford and Kuniasnsky 2002), (Bair and Lahm 2006)], all of which are based on the Bouwer and Rice (1976) method for determining the hydraulic conductivity of an unconfined aquifer. The Bouwer and Rice method uses measurements of well geometry and the water level recovery over time to estimate the near-well hydraulic conductivity. Well characteristics used include the casing radius, length of well screen, well depth, and boring radius. Slug test measurements of initial water surface level, total water surface displacement, and the rate of water level recovery are utilized, along with an estimated effective radial distance found by type-curve matching to empirical values. These properties are then used in an equation to calculate the hydraulic conductivity. The three techniques offer various enhancements to the Bouwer and Rice method.

Each slug test was analyzed using the three techniques. Table 2.8 summarizes the hydraulic conductivity results by analysis technique and provides the statistics when all techniques are combined. Hydraulic conductivity values for fine sand to coarse sand and gravel (the main grain sizes observed during drillin) are typically 1 – 1,000 ft/day (Domenico and Schwartz, 1998). The calculated hydraulic conductivity values are towards the lower end of that range and are below the values calculated from an alluvial/outwash aquifer pumping test conducted in 2008 by Nestle Waters North America™. An aquifer pumping test determines hydraulic conductivity by stressing an aquifer through high rate pumping, while monitoring drawdown in distant wells. This approach measures hydraulic conductivity over a scale of hundreds or thousands of feet rather than over a radius of a few feet as in the case of a slug test. The slug tests resulted in hydraulic conductivity estimates of around 1 - 100 ft/day, compared to 116 - 177 ft/day from the Nestle pumping tests. Values obtained from slug tests are considered less representative than those for an aquifer test (Schwartz and Zhang 2003) and should virtually always be viewed as the lower bound on the hydraulic conductivity of the formation in the vicinity of the well (Butler 1998). Thus, the slug test results are broadly consistent with the aquifer test results. Overall, the three analytical techniques used with the slug tests give similar results. Low seasonal variability also provides some confidence in the testing methods. However, estimates can only be expected to be within a factor of two of the actual conductivity in the vicinity of the well, and ineffective well development can generate error by an order of magnitude or more (Butler 1998).

Table 2.8: Summary of hydraulic conductivity values calculated from slug tests in monitoring wells in the UARB study region.

Analytical Techniques	*January Average (ft/day)*	*July Average (ft/day)*
Bair and Lahm	30.5	16.7
Butler and Garnett	26.9	26.6
Halford and Kuniasnsky	26.7	22.3
Overall Statistics	*January (ft/day)*	*July (ft/day)*
Minimum	3.4	0.2
Maximum	83.8	81.4
Average	28.2	21.8

2.3.3 Water Quality in the UARB Study Region

The chemical quality of surface water and groundwater is influenced by many factors, including effects from the interface between surface water and groundwater. The overall chemical quality of water often is often broadly characterized by the concentration of TDS, with a smaller concentration reflecting better quality (Crouch et al. 1984). TDS is an important consideration for drinking palatability and overall hydrologic system health. However, even if TDS is low, quality may be poor due to high concentrations of individual pollutants.

Surface water quality is affected spatially and temporally by snowmelt and precipitation runoff, groundwater flow, mine drainage, reservoir releases, surface and subsurface chemical reactions, physical weathering, and water use. Groundwater generally has a higher concentration of TDS due to the longer contact time and exposure to variable underground geologic formations and their subsequent dissolution and due to evaporative concentration that occurs near the ground surface. As a result, different aquifers can have widely varying water quality. The water quality in the alluvial aquifer, which is near the surface, depends on the quality of the infiltration water from rain, melting snow, applied irrigation, upflux due to evapotranspiration, and stream interaction. It also is influenced by the chemical composition of the soil and rocks, the rate and distance of water movement, chemicals infiltrating from the surface, the temperature and pressure in the aquifer, and other processes such as ion exchange, oxidation and reduction, and adsorption and desorption (Crouch et al. 1984). Characterization of water quality in the UARB study region is discussed from three perspectives: diagnostic in-situ measurements, laboratory results for tested constituents, and analysis of TDS.

2.3.3.1 In-Situ Water Quality Measurements in the UARB Study Region

At surface water sites, a total of 372 visits were made to record in-situ measurements. Table 2.9 shows summary statistics for all sites together. A total of 60 visits were made for different locations and times in the Arkansas River, and a total of 312 visits were made for tributary sites. Results of in-situ measurements are within expected ranges for an intermontane river basin and usually reflect good water quality. The tributaries generally have a broader range of values than the main stem. Values of pH between 6.5 and 9.0 have been established as acceptable for aquatic life and for recreational contact, while domestic water supply requirements range from 5.0 to 9.0 (CDPHE 2010). Some stream measurements fall outside this range, but the 15^{th} and 85^{th} percentile values fall within this range at 7.5 and 8.2, respectively.

Table 2.9: Summary statistics of in-situ water quality measurements at surface water sites in the UARB study region.

	EC	*pH*	*DO*	*ORP*	*T*	
All Sites	*(µS/cm)*		*(mg/L)*	*(mV)*	*(°C)*	*(°F)*
Minimum	22	6.1	6.5	17	-0.2	31.7
Maximum	336	9.3	16.0	295	23.5	74.3
Average	132	7.9	9.9	168	7.3	45.2
Arkansas River Sites						
Minimum	22	6.2	7.0	22	0.0	32.0
Maximum	231	8.9	15.0	295	18.0	64.4
Average	153	8.1	10.2	179	7.9	46.3
Tributary Sites						
Minimum	23	6.1	6.5	17	-0.2	31.7
Maximum	336	9.3	16.0	291	23.5	74.3
Average	128	7.8	9.8	166	7.2	45.0

DO measurements across all sites are above the 3.0 mg/L required in Colorado surface waters for domestic, agricultural, and recreational purposes, and they rarely are below the more stringent 6.0-7.0 mg/L that is recommended for aquatic life (CDPHE 2010). DO varies seasonally, as expected from an inverse relationship with *T* (Figure 2.28). January had the highest average measured DO (16.0 mg/L) corresponding with the second lowest average *T* value (31.9 °F). July had the lowest average DO (6.5 mg/l) coinciding with the highest average *T* value (74.3.5 °F). The sites at Chalk Creek near Nathrop and Clear Creek below Clear Creek Reservoir had consistently higher *T* than average during the winters over the study period. Chalk Creek is located in a region of geothermal heat sources. Below Clear Creek reservoir, *T* is influenced by the more stable reservoir *T*, which is above the overall winter surface water average due to insulating ice cover. Consequently, the average *T* (42.8 °F) and DO (11.0 mg/L) for these two sites during January and February are noticeable higher than the overall average for that time, which may explain the one month discrepancy between lowest *T* and highest DO. Another anomaly to note is the unexpected rise in DO in August. Unexpectedly high average DO (10.6 mg/L) was measured in August 2009. The August 2010 average DO (8.4 mg/L) and the values measured in neighboring months in both years,7.7 mg/L in July and 8.4 mg/L in September suggest that an equipment or operator error influenced DO measurements in August 2009.

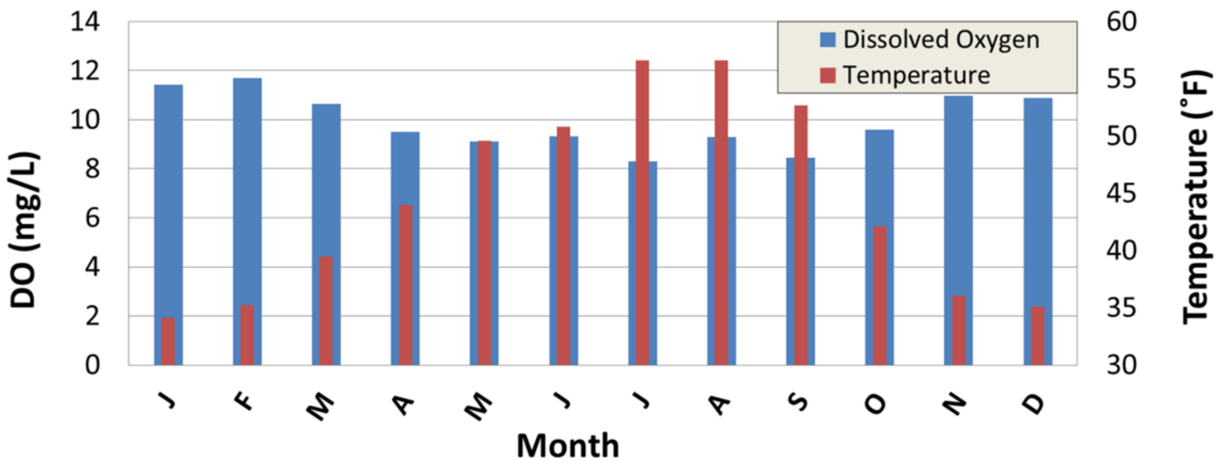


Figure 2.28: Temporal comparison of DO to temperature from 366 surface water measurements.

At groundwater monitoring sites, a total of 434 visits were made to make in-situ measurements. Table 2.10 displays summary statistics for these measurements. Data on *T* were compiled from the hourly readings stored by the pressure transducer data loggers rather than the monthly multiprobe measurements. The data loggers provide a temperature dataset with higher temporal resolution, and the data are more reliable because the temperature is measured in the well.

Table 2.10: Range and average values of routine monthly in-situ water quality measurements and of hourly transducer measurements of temperature in groundwater monitoring wells in the UARB study region.

	EC	*pH*	*DO*	*ORP*	*T*	
	(µS/cm)		*(mg/L)*	*(mV)*	*(°C)*	*(°F)*
Minimum	109	4.8	0.1	-314	22.5	40.3
Maximum	436	8.9	15.0	353	41.7	59.5
Average	250	7.0	6.2	212	32.0	49.8

Values for EC, pH, ORP, and *T* are within expected ranges and generally reflect good water quality. Colorado groundwater regulations for pH in domestic drinking water supply stipulate a range of 6.5 – 8.5 (CDPHE 2009). The 15th percentile of the pH readings is 6.4, falling just outside of this range, reflecting the possible need for some caution regarding pH levels in domestic well water supplies. Overall, DO readings were surprisingly high. The average DO value is 6.2 mg/L. Some wells had consistently high values, suggesting several possible causes. A higher DO could be the result of a shallow water column in the well, which would cause the in-situ measurement to be taken near the air/water interface. A raised DO level also may indicate that the aquifer is well-connected to surface water recharge sources with higher DO. High DO values could also result from highly fluctuating water table levels, which trap air that can partially dissolve into the water. Finally, high DO could be the result of the physical properties of the vadose zone and the alluvial geology. Perhaps microbial respiration and decomposing organic matter is limited, which results in relatively high DO levels compared to those in the recharge sources (Rose and Long 1988).

Groundwater *T* over the study period ranged from 40.3˚F to 59.5˚F, with an overall average of 49.8 ˚F. Most wells showed temporal variability as well as local influences as illustrated in Figures 2.22, 2.23 and 2.24. The highest average *T* values, near 53.2˚F, were in three wells located the farthest downstream, in the Sand Park area near Salida. Unlike the surface water measurements, no obvious geothermal influence on water temperatures was observed for the area near Chalk Creek or Cottonwood Creek on the western valley floor, where geothermal exploration and commercial hot springs are located. The coolest average *T* value (46˚F) was recorded in two wells located near Gas Creek and Browns Creek. The two wells located farthest upstream also had slightly lower than average annual *T*. At a given well, *T* ranges were as little as 0.4 ˚F and as high as 13.4 ˚F over the study period. Over the well network as a whole, the average annual temperature range was about 6.2 ˚F. For the ten wells showing irrigation influence, the average range was 8.3 ˚F, including four wells with ranges over 12.5 ˚F (e.g., Figure 2.24).

2.3.3.2 Laboratory Analysis of Water Samples in the UARB Study Region

Water samples were gathered from monitoring sites in July 2009, November 2009, May 2010, August 2010, and November 2010. All samples were analyzed for dissolved constituents: specific cations and anions, selenium, and uranium. For two of these sampling events (May 2010 and November 2010), a subset of sites were analyzed for additional dissolved elements including: zinc, copper, iron, manganese, cadmium, aluminum, fluoride, and lead.

2.3.3.2.1 Individual Chemical Constituents in the UARB Study Region

For each surface water sampling event, the routine sites as well as some non-routine sites were visited resulting in a total of 143 water quality samples, including 20 duplicates. The routine site samples and a small subset of the non-routine site samples were additionally analyzed for the specific elements group, totaling 45 samples, of which 6 were duplicates. Results of duplicate sample analyses indicated concentration values close or equal to principal samples' concentration values.

Table 2.11 is a summary of laboratory results for the entire surface water sampling dataset. Results of the laboratory analysis for Se concentration, C_{Se}, showed a minimal presence with levels at or below the reporting limit of 0.4 µg/L. U was detected in most samples, with U concentration, C_U, generally increasing downstream for all tributaries and the main stem. The Browns Creek downstream site and the South Arkansas River downstream site had the highest average uranium concentrations at 4.7 µg/L and 3.4 µg/L, respectively. In the Arkansas river sites, U increased from an average 0.3 µg/L at Granite to 2.3 µg/L at Salida. The national primary drinking water regulation for maximum contaminant level of total recoverable uranium in public water supplies is

30 μg/L (USEPA 2009), while the human health-based value in Colorado is 16.8 μg/L (CDPHE 2010). Thus, U is not currently of concern in the sampled locations in the UARB study region. Specific salt ion concentrations have levels well below recommended limits and generally reflect high water quality.

Results of the additional elements analysis show generally low values and reflect high quality water. Three measurements, denoted by highlights in Table 2.11, are discussed in further detail. The dissolved Pb concentration in a sample from the Clear Creek upstream site resulted in a value of 144 μg/L during the low-flow November 2010 sampling, but the same site registered non-detectable levels in May 2010. Colorado water supply regulations limit total recoverable Pb concentration to 50 μg/L for domestic supply (CDPHE 2010), meaning that just the dissolved fraction of lead in the water is almost three times the limit and the total recoverable certainly would be even higher. Flow measurements during the sampling events were 35 ft^3/s and 17 ft^3/s in the May and November site visits, respectively. Based upon the gage downstream, measuring flow into Clear Creek Reservoir, 17 ft^3/s is very near the lowest (base flow) flow while 35 ft^3/s is likely influenced by some precipitation runoff. In comparison, the annual snowpack runoff peaks above 300 ft^3/s. This high Pb concentration at 17 ft^3/s versus no detection at 35 ft^3/s suggests the lab result could be a measurement error or it might suggest a much higher concentration of Pb in the base flow versus a more diluted precipitation driven flow. Regardless of the source, the upper reaches of Clear Creek should be considered for future Pb analysis during base-flow conditions and at other times of the year if possible. Excluding this seemingly anomalous result, the average Pb value from 43 other surface samples in the study region is 0.16 μg/L.

Fl tested slightly above the domestic water supply regulatory limit of 2.0 mg/L (CDPHE 2010) at the downstream Browns Creek site for both its primary and duplicate samples, with identical results of 2.3 mg/L. A Mn concentration of 0.23 mg/L was measured in Fourmile Creek during low flow in November 2010 with a corresponding value of 0.04 mg/L in May 2010. The EPA secondary drinking water regulation for Mn is 0.05 mg/L (USEPA 2009). Two additional locations resulted in individual Mn concentrations at the limit (0.05 mg/L), including the downstream Browns Creek site in May 2010 and Clear Creek below Clear Creek Reservoir in November 2010.

The most current CDPHE report submitted to the EPA, effective April 30, 2010, indicates that no surface waters in the study region are on Colorado's section 303(d) impaired list, which otherwise would require monitoring and evaluation to derive a Total Maximum Daily Load (TMDL) (CDPHE 2010). Waters in the study region with a previously established TMDL per the CDPHE and registered with the EPA as of a June 2009 assessment include the main stem of the Arkansas River and Chalk Creek (CDPHE 2009). The impaired main stem river segment stretches from Lake Creek, upstream of the study area, to Lake Pueblo, many miles downstream of the study area, where the river exits the mountains onto the eastern plains. The Chalk Creek segment consists of its main stem from headwaters to its confluence with the Arkansas River. The Arkansas River is regulated by a TMDL for Cd and Zn, while Chalk Creek is regulated for Pb and Zn, all of which threaten the Aquatic Life Cold 1 use classification (CDPHE 2009). Designations for use in recreation, agriculture, and water supply are not listed as impaired. Determination of aquatic life impairment from dissolved concentration of the elements sampled is determined through statistical analysis of multiple samples over a six-year period (CDPHE 2011). Few samples were available for analysis so a simplified approach was applied. For the minimal numbers of samples collected, the more-stringent chronic level concentration was calculated for comparison to actual lab-determined element concentrations. Chronic level concentrations were determined using CDPHE equations, which are a function of the hardness, as reported by the laboratory for the pertinent sample.

Table 2.11. Surface water quality sampling results in the UARB study region, summarizing the concentration, C_i, of each constituent *i*. Some values of possible concern are shown shaded (ND is Not Detected).

	C_{Se} (µg/L)	C_U (µg/L)	C_{Na} (mg/L)	C_K (mg/L)	C_{Ca} (mg/L)	C_{Mg} (mg/L)
Minimum	0.1	ND	1.0	1.0	4.0	1.0
Maximum	0.4	15.1	13.0	3.0	37.0	8.0
Average	0.3	1.9	3.2	1.0	15.1	2.8
	C_{NO_3-N} (mg/L)	C_{SO_4-S} (mg/L)	C_{Cl} (mg/L)	C_{CO_3} (mg/L)	C_{HCO_3} (mg/L)	*Hardness* (mg/L)
Minimum	0.1	0.2	1.0	1.0	6.0	8.0
Maximum	6.0	12.0	3.0	43.0	137.0	126.0
Average	0.2	4.6	1.3	2.0	52.9	53.1
	Alkalinity (mg/L)	C_B (mg/L)	C_{Al} (µg/L)	C_{Cd} (µg/L)	C_{Pb} (µg/L)	C_{Cu} (mg/L)
Minimum	5.0	ND	ND	ND	ND	ND
Maximum	148.0	0.0	60.3	0.1	144.0	0.03
Average	45.0	0.0	2.6	0.0	3.4	0.01
	C_{Zn} (mg/L)	C_{Fe} (mg/L)	C_{Mn} (mg/L)	C_{Fl} (mg/L)		
Minimum	ND	ND	ND	0.09		
Maximum	0.07	0.44	0.2	2.3		
Average	0.01	0.06	0.02	0.69		

For three monitoring points along the Arkansas River, out of nine samples, including duplicates, only one sample was close to the chronic levels for any of the elements tested. At the Granite site in May 2010, the dissolved Cd concentration (0.25 µg/L) was detected at a level very near the chronic limit (0.28 µg/L) but was quite less than the acute limit of (1.7 µg/L). For Chalk Creek, one sample was drawn from the upstream and downstream sites for both the May 2010 and November 2010 sampling events. The downstream site results showed element concentrations at only a fraction of the chronic levels for impairment. At the upstream site on Chalk Creek, Cd, Pb, and Zn occurred in concentrations exceeding chronic levels, while the other elements occurred at levels below chronic. Laboratory results and calculated chronic and acute impairment concentrations of Cd, Pb, and Zn for the Chalk Creek upstream site are shown in Table 2.12. All three constituents exceeded chronic levels in the May 2010 sampling, but remained below acute levels. All concentrations were reduced during the low-flow November 2010 sampling, with no values exceeding chronic levels. Results suggest the need for continued monitoring of these constituents, in particular Cd since it is not included in the 303(d) listing. Results for Pb, and Zn reflect the impairment listings. These constituents are under scrutiny by the EPA and CDPHE with ongoing remediation investigations in an effort to reduce them below their TMDLs. Interpreting these results as loads, the May goal for TMDL of lead in Chalk Creek is 0.22 lbs/day (CDPHE 2009), while the load determined from the sample and the measured discharge was 0.46 lbs/day. May and June are the two months of the year in which load reductions in Pb are required, based on studies by the CDPHE. The calculations for chronic level aquatic life impairment were made also for the other surface water samples. No other samples revealed results above the chronic impairment levels.

Table 2.12: Chalk Creek (upstream site) dissolved constituent concentrations of concern.

Sample Date	*Flow Rate (ft^3/s)*	*C_{Cd} (µg/L)*			*C_{Pb} (µg/L)*			*C_{Zn} (µg/L)*		
		Sample	*Chronic*	*Acute*	*Sample*	*Chronic*	*Acute*	*Sample*	*Chronic*	*Acute*
May 2010	74	0.42	0.24	1.45	1.14	1.12	28.80	70	66.5	76.7
Nov. 2010	17	0.19	0.26	1.58	ND	1.25	32.15	70	72.3	83.4

For groundwater, the 17-well network was sampled when water column depths and access permitted, which produced a total of 135 water quality samples (including duplicates). In May 2010 and November 2010, 29 samples from a subset of the monitoring wells were analyzed for the suite of additional elements. Table 2.13 shows a summary of results for those groundwater samples. Overall, as in the surface water samples, the concentrations of elements and other constituents sampled were low and reflect good water quality. However, in a single well, samples surpassed the Mn concentration threshold of 0.05 mg/L, which is the domestic groundwater supply standard in Colorado (CDPHE 2009). Also, presence of Fl is notable but below the maximum contaminant limit of 4.0 mg/L in all samples (CDPHE 2009). The mean hardness level is in the *moderately hard range* of 61-120 mg/L (Durfor and Becker 1964), which is near or less than would be expected for groundwater and does not constitute a health or quality concern.

Like the surface water results, a presence of U was found throughout the region in groundwater samples. Two monitoring wells, located in the same vicinity near the downstream ends of Browns Creek and Gas Creek, had the highest levels with values just below the maximum contaminant limit of 30 µg/L (USEPA 2009). Figure 2.29 shows a plot of estimated uranium concentrations throughout the rift valley, based upon an inverse-distance weighted interpolation between measurement locations. This analysis of the limited data likely does not accurately portray the geological diversity and possible localized high uranium concentration areas that may exist but were not observed. The figure does display higher U concentrations in the lower areas of the Browns Creek and Gas Creek watersheds, along with slightly elevated levels in the southern end of the main valley. Elevated U concentrations in the surface water samples in Browns Creek, Gas Creek, and the South Arkansas River appear to coincide with the pattern in this map, which further supports the presence of stream-aquifer interaction.

Table 2.13: Water quality sampling results from groundwater monitoring wells in the UARB study region, summarizing the concentration, C_i, of each constituent i. Some values of possible concern are shown shaded (ND is Not Detected).

	C_{Se} (µg/L)	C_U (µg/L)	C_{Na} (mg/L)	C_K (mg/L)	C_{Ca} (mg/L)	C_{Mg} (mg/L)
Minimum	0.0	0.0	2.0	1.0	12.0	1.0
Maximum	2.5	27.6	74.0	4.0	64.0	14.0
Average	0.5	4.6	11.2	1.6	34.8	5.0
	C_{NO_3-N} (mg/L)	C_{SO_4-S} (mg/L)	C_{Cl} (mg/L)	C_{CO_3} (mg/L)	C_{HCO_3} (mg/L)	*Hardness* (mg/L)
Minimum	0.1	2.0	1.0	1.0	36.0	34.0
Maximum	5.5	22.0	35.0	6.0	221.0	194.0
Average	1.0	7.0	3.7	1.1	119.3	106.0
	Alkalinity (mg/L)	C_B (mg/L)	C_{Al} (µg/L)	C_{Cd} (µg/L)	C_{Pb} (µg/L)	C_{Cu} (mg/L)
Minimum	30.0	0.0	0	0	0	0.01
Maximum	181.0	0.5	0	0	0	0.03
Average	98.0	0.0	0	0	0	0.01
	C_{Zn} (mg/L)	C_{Fe} (mg/L)	C_{Mn} (mg/L)	C_{Fl} (mg/L)		
Minimum	0.01	0.01	0.01	0.09		
Maximum	0.14	0.01	0.42	2.13		
Average	0.02	0.01	0.04	0.93		

In the Browns Creek watershed, the upstream monitoring station and the monitoring well in the upper end of the creek's irrigated valley both have little or no U presence, with average concentrations of 0.8 µg/L and 1.8 µg/L, respectively. At the downstream Browns Creek station and groundwater monitoring well, the averages are 4.7 µg/L and 12.6 µg/L, respectively. Gas Creek was sampled only one time but shows a U concentration increase from 5.9 µg/L at the upstream sample site to 15.1 µg/L at the sample site 1.7 mi downstream. These measurements suggest a U source in the vicinity that may be worthy of further study.

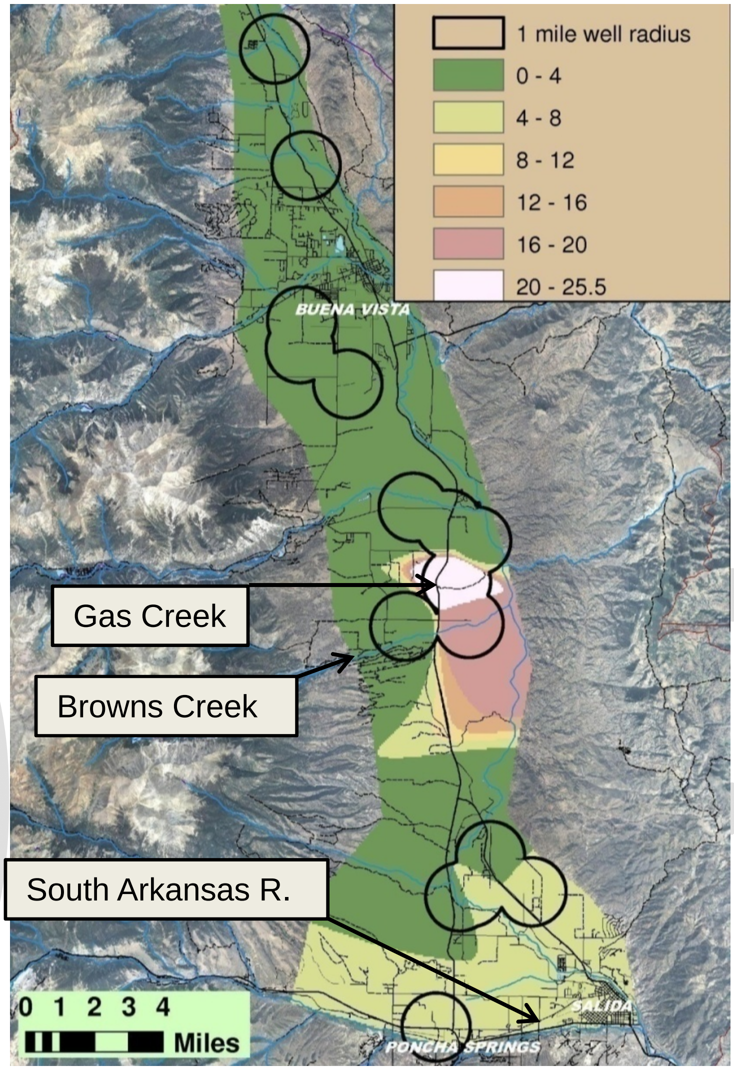


Figure 2.29: Estimated contours of groundwater C_U (µg/L) in the UARB study region.

Overall, water quality at surface and ground sites of the UARB is quite good for the constituents and locations tested. The data support the need for some continued monitoring of uranium and for occasional testing for Mn, Pb, Cd, and Fl in addition to monitoring the TMDLs in Chalk Creek and the Arkansas River. The downstream portion of the Browns Creek and Gas Creek watersheds may also merit continued monitoring for U. The presence of elevated levels of U, Mn, and Fl in this area may suggest a distinct local geology or an interaction between the shallow and deep aquifers that merits enhanced study.

2.3.3.2.2 Total Dissolved Solids in the UARB Study Region

TDS is a measure of the combined content of all dissolved inorganic and organic substances. It is an important component in determining overall water quality, river health, suitability for irrigation, effects on piping systems, and water treatment requirements. TDS can come from organic sources such as leaves, plankton, industrial waste, and sewage as well as runoff from urban areas with associated road salts, fertilizers, and pesticides (HM Digital 2011). Inorganic contributors can include mineral springs, CO_3 deposits, salt deposits, geologic weathering and erosion, and brackish deep-aquifer water intrusion (Oram 2011). Analysis of TDS throughout the study region is helpful to determine spatial patterns, temporal dynamics, and possible aquifer-stream interactions.

TDS has been calculated for solutions that passed through the 0.45 µm filter during sampling as the sum of the concentrations of Na, K, Ca, Mg, NO_3, SO_4, Cl, CO_3, and HCO_3 (in units of mg/L) as determined by laboratory analysis for each of the seven sampling events. In instances where duplicate samples were taken, an average of the two calculations was used to represent that location and date. The difference between primary and duplicate sample TDS values ranged from 0 to 14 mg/L, with an average difference of 5.0 mg/L for 21 sets of duplicates. The EPA sets the maximum contaminant level of TDS for drinking water as 500 mg/L (USEPA 2009), and the palatability is rated as excellent for water with TDS levels less than 300 mg/L (WHO 1996). TDS guidelines for irrigation water vary according to crop and other conditions (Wallender and Tanji 2012). Statistics of the TDS estimates from the study region are shown in Table 2.14. These values indicate good overall water quality, but they suggest that groundwater has a markedly higher average TDS concentration.

Table 2.14: Summary statistics of TDS in water samples from the UARB study region.

Statistic	*Surface Water TDS (mg/L)*	*Groundwater TDS (mg/L)*
Minimum	33.9	80.3
Maximum	231.4	343.8
Average	93.5	202.9

For surface water, the primary dissolved constituents that contribute to the TDS concentration in the Arkansas River are HCO_3, SO_4, and Ca. The contributions of these constituents are 57%, 15%, and 18% of the total, respectively. The major contributing constituents in the tributaries are also HCO_3, SO_4, and Ca, which contribute 58%, 13%, and 18%, of the total, respectively. When comparing the contributions of these compounds between sites, the only apparent trend was an inverse relationship between HCO_3 and SO_4. As the HCO_3 contribution increases, the SO_4 contribution decreases proportionately.

For determination of general water type, the concentrations of the dissolved major cations (Ca, Mg, K, and Na) and dissolved major anions (NO_3, SO_4, Cl, CO_3, and HCO_3) were converted from mg/L to milliequivalents per liter (Hem 1985). A cation or anion with proportion greater than 50% of the total milliequivalents per liter is deemed the predominant anion or cation and describes the water type. If no constituent contributes 50% or more of the total, the water type is mixed. Surface water samples predominantly reflect a Ca- HCO_3 water type. The dominant cation is Ca without exception. In four tributaries, the upstream sampling sites show some dominant-anion variability with alternating SO_4 and HCO_3 dominance from sample to sample.

The highest average surface water TDS (193 mg/L) in the study region occurs at the downstream site of the South Arkansas River. The lowest average (39 mg/L) occurs at the upstream site on Browns Creek. In the Arkansas River, the TDS peaks at the downstream gage in Salida with an average value of 106 mg/L. The average rate of TDS increase is 0.5 mg/L per mile from Granite to Nathrop and 1.3 mg/L per mile from Nathrop to Salida. Interestingly, the second highest average TDS (123 mg/L) occurs at the downstream Browns Creek site, meaning this stream has by far the highest rate of increase in TDS (16 mg/L per mile) as it flows over a distance of only about 5 mi. The South Arkansas River has the second highest rate of increase (9 mg/L per mile) rising from an average of 97 to 193 mg/L over approximately 11 mi. Chalk Creek only increases at a rate of about 2 mg/L per mile from an average of 77 to 105 mg/L in approximately 11 mi.

Overall, TDS concentrations in the tributaries and main stem are relatively low. The Browns Creek spatial gradient and the higher values at the downstream end of the South Arkansas River and the Arkansas River might occur because these waterways approach the edge of the rift valley and its associated fill, which forces more groundwater to the surface. This geologic feature, the natural accumulation of inorganic and organic TDS loading, and evaporative concentration in the downstream direction are likely explanations for these observations.

For the monitoring wells, the primary dissolved constituents as a percent of the calculated TDS concentration are again HCO_3, SO_4, and Ca in proportions of 59%, 3%, and 18%, respectively. These percentages are very similar to those in the tributaries. The water type in the wells is predominantly Ca- HCO_3. The close similarity between the alluvial/outwash groundwater and the surface water again suggests interconnectivity.

A well located near Salida (500822-02), which has the second highest average TDS, has a constituent makeup notably different from all the other wells. At this well, the water type is Na with mixed dominant anions of SO_4 and HCO_3. The primary dissolved constituents are HCO_3 (36%), Na (23%), SO_4 (6%), and Cl (9%). This well is also the deepest well in the network and has one of the most static water table depths, staying between 10 and 13 ft below ground surface throughout the study period. These observations suggest that this well may be penetrating a deeper aquifer.

The highest average TDS (312 mg/L) in the well network occurs in the most southeastern well, while the lowest average value (86 mg/L) occurs in the northernmost well. The second and third highest along with the lowest average TDS wells also are located in the southeastern region. Overall, the well network generally reflects rising TDS in the downstream direction. The Browns Creek valley shows similar TDS patterns for groundwater and surface water. The average TDS more than doubles between the western (up-gradient) monitoring well (119 mg/L) and the eastern monitoring well (275 mg/L).

2.3.3.2.1.1 EC to TDS relationships in the UARB Study Region

EC was measured during every site visit, but TDS only was available from laboratory sample analysis. Identifying relationships between TDS and EC can provide for expanded determination of TDS values and subsequent analysis of mass loading and flux. Such relationships (if present) are expected to depend on both water *T* and the proportions of the various compounds, anions, and cations making up the dissolved solids (Oram 2011). However, by measuring EC as specific conductance at 25°C , the dependence on *T* can be removed. Regional and site specific analyses were completed to produce equations that can be used to approximate TDS values using the EC measurements. Figure 2.30 is a plot of TDS and EC for all surface water and groundwater samples. The surface water and groundwater data both indicate linear relationships. The coefficients of determination (R^2) for both datasets are high, and both relationships are statistically significant (α = 0.05).

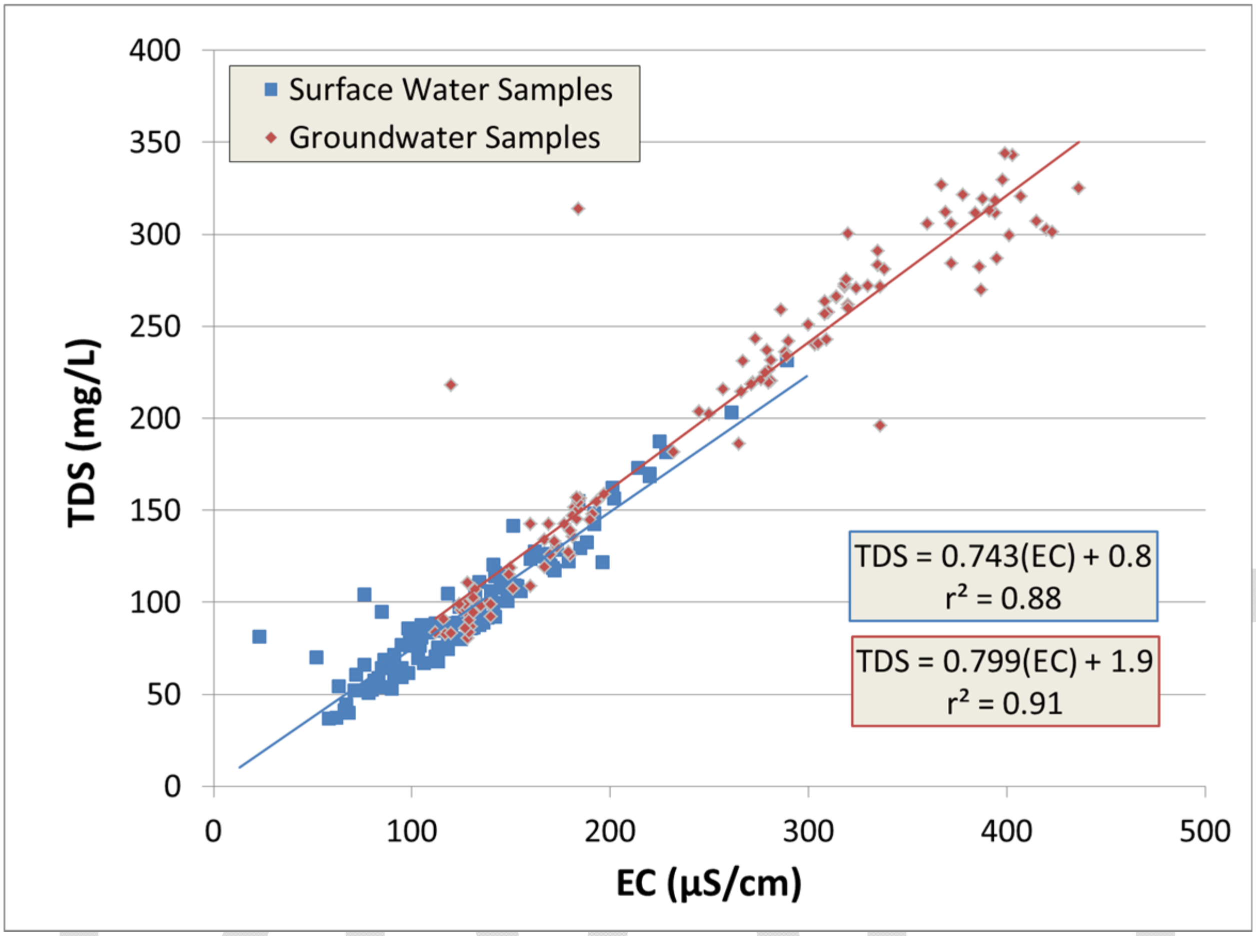


Figure 2.30. EC-TDS relationships for surface water samples and groundwater samples in the UARB study region.

EC-TDS data were also analyzed at individual sites to explore site-specific relationships. At individual surface sites with four or more samples, plots of TDS to EC show high correlation. For 11 of 16 sites, the values for R^2 were higher than 0.90. Only two sites resulted in an R^2 value below 0.78. For the Arkansas River sites, the relationships of TDS to EC are given by

$$TDS = 0.765\,(EC) - 8.4 \tag{2.2}$$
$$TDS = 0.750\,(EC) + 5.1 \tag{2.3}$$
$$TDS = 0.825\,(EC) - 14.3 \tag{2.4}$$

for the Granite, Nathrop, and Salida sites, respectively. In these equations, TDS is in mg/L and EC is specific conductance in µS/cm. The R^2 values are 0.85, 0.94, and 0.98 for the three equations, respectively.

For monitoring wells, individual sites generally had lower R^2 values. For 5 of 17 wells, R^2 values were above 0.90, while the average r^2 for all individual groundwater sites was only 0.57. The coefficient of variation (CV) for TDS values over sampling events at individual well sites ranged from 2% to 43%, with an average of 13%.

Site-specific equations based on only four or five samples are likely poor representations for conclusive EC-TDS relationships, and any results should be treated with appropriate skepticism.

However, use of the general surface and groundwater EC-TDS regression equations developed in Figure 2.30 seem to represent well the groundwater and surface waters in the study area as a whole.

The regression lines in Figure 2.30 are nearly parallel and only slightly offset, which implies that the EC-TDS relationships are similar for the alluvial/outwash groundwater and surface water. The slight difference in the regression lines is likely due to the ion composition differences of the surface and groundwater, which are slightly different proportions of HCO_3, SO_4, and Ca. The similar regression lines further supports the conclusion that the alluvial/outwash aquifer and surface waters are interconnected.

2.3.3.2.1.2 TDS Mass Loading in the UARB Study Region

The product of TDS concentration and discharge yields the TDS mass loading. Analysis of mass loading dynamics can provide insights into the sources of TDS loading. Furthermore, if a relationship between TDS and gage-measured discharge occurs, then continuous mass loading estimates can be obtained. This broader analysis of mass loading dynamics might provide additional insights into aquifer-stream interactions.

TDS concentrations in the main stem increased moving downstream. Based upon the seven laboratory samples from each site, the TDS increased from an average of 82 mg/L at Granite to 106 mg/L at Salida. To evaluate contributing surface water sources of mass load, the inflows from tributaries to the main stem must be delineated. Of the six monitored tributaries, all but the South Arkansas River join the main stem in the reach between Granite and Nathrop. From the Nathrop gage to the Salida gage, there are no perennially flowing tributaries.

Using TDS concentration data from the seven sampling expeditions and gage discharge estimates on the day of the sampling, TDS load in tons per day was calculated. Analysis showed that the TDS mass load increased an average of 88% (range is 55% to 120%) or 63 t/day from Granite to Nathrop and 17% (range is -7% to 43%) or 22 t/day from Nathrop to Salida. The monitored tributaries contributed an average of 35% (range is 21% - 45%) of the 63 t/day TDS load increase from Granite to Nathrop. Clear Creek, Fourmile Creek, Cottonwood Creek, Chalk Creek, and Browns Creek are the tributaries in this reach and contribute an average of 12%, 1%, 7%, 14%, and 3% of the 63 t/day load increase, respectively. Overall, this analysis suggests that well over half of the TDS load increase moving downstream is provided by sources other than the monitored tributaries.

The analysis of mass load dynamics can be extended beyond the seven sampling events if a relationship between TDS and discharge can be determined. Plots of TDS concentration versus flow rate, Q, for the three Arkansas River monitoring sites are provided in Figure 2.31. Solid data points show TDS values calculated from the sum of laboratory-reported constituent concentrations, while the outlined data points show TDS values determined from the site-specific EC-TDS regression equations (Equations 2.2 – 2.4).

For off-season discharge values at the Nathrop gage, the available staff level readings (when ice did not impede) were converted to discharge using the USGS published stage-discharge relationship as of January 7, 2011 assuming zero shift adjustment. This method for determining discharge was used for 5 of the 14 Nathrop points in Figure 2.31. This method likely results in some error in the estimated discharge. The staff is mounted to the outside of the stilling well and is not necessarily calibrated to the float used for the USGS readings. In addition, the assumption of no shift neglects any changes due to flow constrictions or streambed changes.

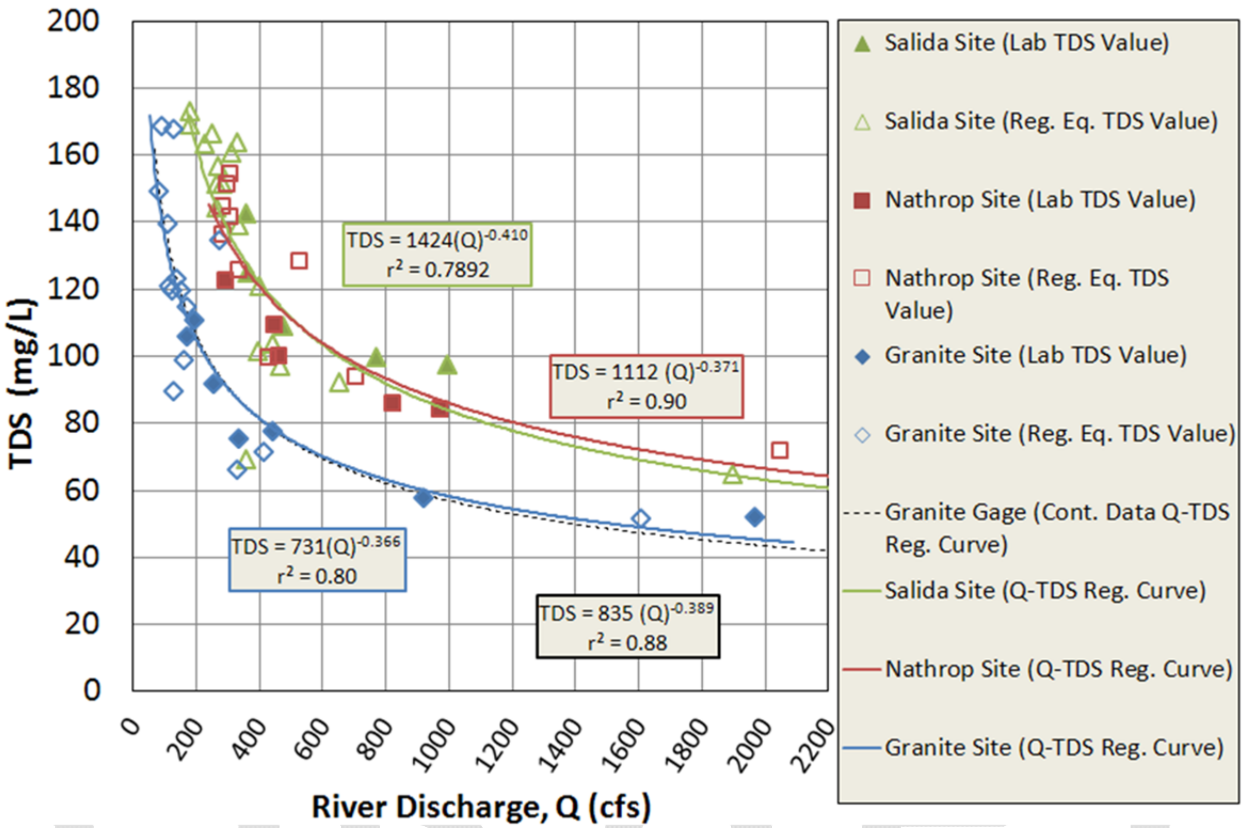


Figure 2.31: Relation of TDS to *Q* at three Arkansas River stations in the UARB study region.

The CDWR gage at Granite also records EC. Applying the EC-TDS regression for Granite (Eq. 4.2) to the 883 daily-average EC records during the study period, a continuous record of TDS was calculated. These records account for flows during the study period ranging from 68 to 2820 ft^3/s. A *Q*-TDS power-function regression curve was developed (R^2 = 0.88) and is plotted in Figure 2.31. This regression curve closely follows the regression curve developed from the 20 in-situ measurements and provides support for the development and use of such relationships for the other sites. The *Q*-TDS regression curves from all three Arkansas River sites show that TDS decreases, or is diluted, with increasing discharge. A strong association is evidenced by the R^2 values noted in the figure. Using the *Q*-TDS equations displayed in Figure 2.31, TDS can be estimated at each site from the measured flow rate. Note that using the Nathrop and Salida *Q*-TDS equations with discharges above 1,000 ft^3/s is less reliable because each regression curve is developed using a single observation above that value. This further reduces the reliability of the equations for Nathrop and Salida at high discharge values.

Figure 2.32 plots the monthly TDS load at the three Arkansas River sites. It was developed using the average daily discharge values at each site in the *Q*-TDS equations from Figure 2.31 to determine the total TDS load passing by each river gage on a daily basis. The daily values were added to produce monthly values during the study period. The largest increases in load (from upstream to downstream) corresponds to the high-flow summer periods, and the smallest load increases occur during the low-flow winter periods. The monthly load values for the Granite site are based upon the *Q*-TDS regression equation developed using the daily discharge values over the entire study period and are considered the most reliable depiction of load variation. The *Q*-TDS equations used for the Nathrop and Salida monthly loads are more uncertain at high discharge levels, which are typical during the summer months of June and July.

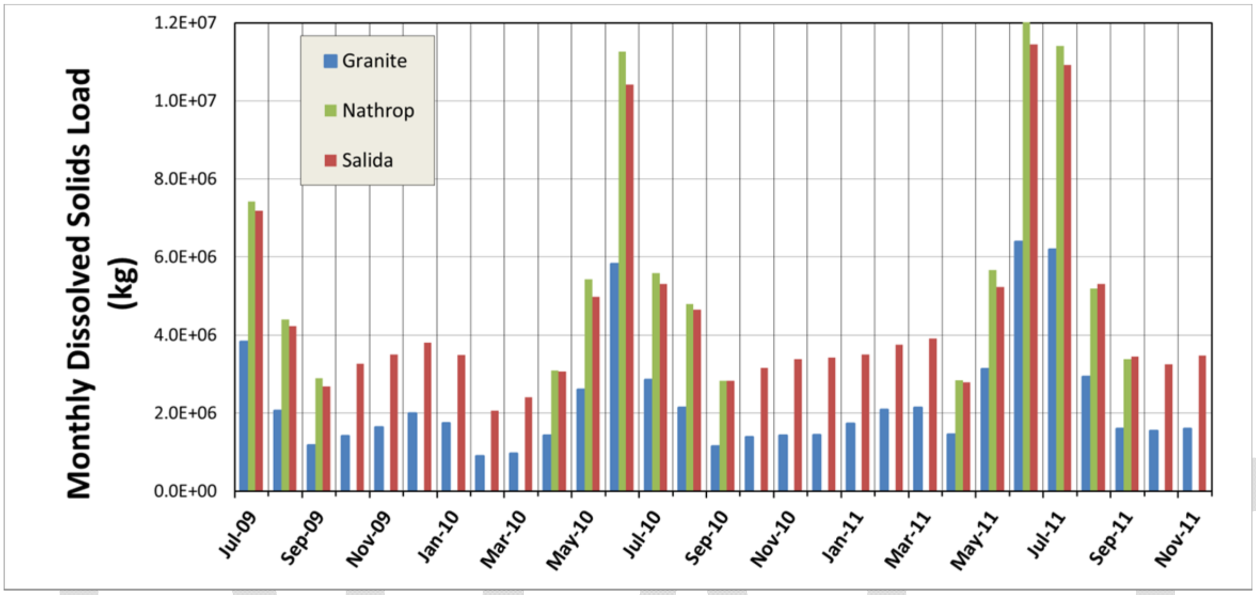


Figure 2.32: Variation in mean monthly TDS load at Granite, Nathrop, and Salida gage sites on the Arkansas River during the study period.

The Nathrop and Salida gages, which are approximately 11.5 river miles apart, had similar monthly loads for the periods when the Nathrop gage was active. At high flows, the plot suggests that the TDS load actually decreased along the reach. However, this is contrary to the load calculations from the seven sampling events, which showed an average load increase of 17% along the reach. The average flow rates during the sampling events at Nathrop and Salida were 599 and 593 ft^3/s, respectively. Because the sampling events occurred during low discharge and discharge often decreases from Nathrop to Salida because of irrigation withdrawals, a load decrease between Nathrop to Salida is possible during the irrigation season. At lower discharge levels, data suggest that the reach has a slight increase in TDS load, likely due to higher-TDS groundwater inflows during this period. The decrease in load also could be a reflection of inaccuracy in the Q-TDS equations for Nathrop and Salida at discharges above 1,000 ft^3/s. Some error was introduced in the Q-TDS equation for Nathrop due to off-season discharge estimates from the staff readings. Higher uncertainty also is reflected in the lower R^2 for the EC-TDS regression equation for Nathrop.

An analysis of the load during the study period is helpful for evaluating possible TDS sources and for attempting to determine if different reaches of the main stem are dominant sources for the TDS loading. Figure 2.33 plots the daily percentage change in TDS load flux for the river reaches between Granite and Salida. TDS load fluxes were calculated from the average daily discharge values at each gage and the *Q*-TDS regression equations. The percent change in the TDS load flux for the whole reach from Granite to Salida and the subreaches from Granite to Nathrop and Nathrop to Salida were calculated. Mean daily discharges at the three gages are shown on the secondary vertical axis for reference.

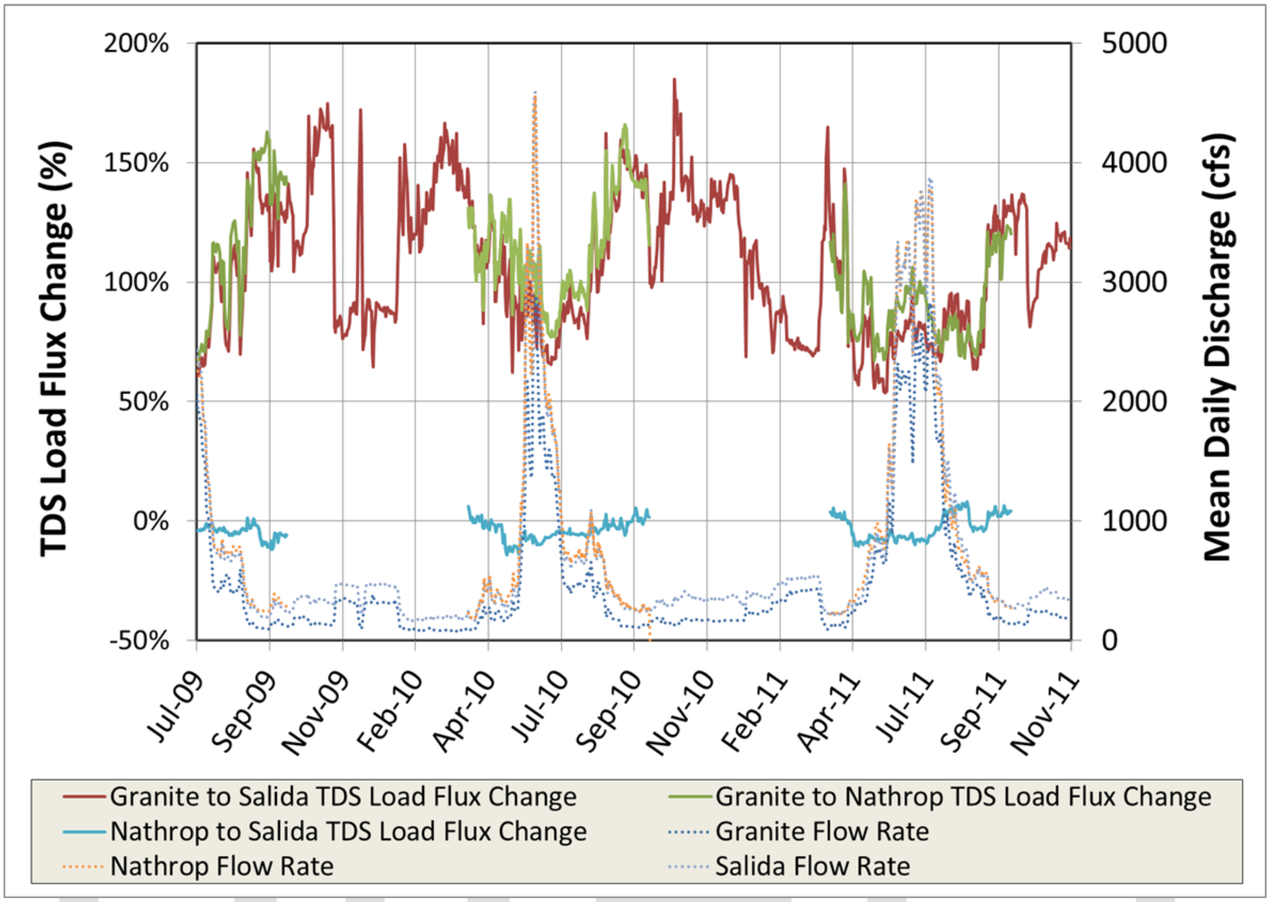


Figure2.33: TDS load flux change along reaches in the study region, with flow rate on the secondary axis for reference.

During the highest flow period the load flux shows its lowest relative increase (around 60% to 80%) between Granite and Salida. This behavior likely is due to the snowpack runoff introducing low TDS water. Conversely, at lower discharge levels, higher load flux increases occur with peaks around 200%. One possible explanation for this behavior is the high TDS loading from groundwater inflows during such periods. During relatively low flow periods where discharge increases slightly (in particular, two periods around November and December 2009), the load flux increase is reduced to about 100%. This behavior might be due to a short-term weather event, such as a warm period causing snowmelt with lower TDS. Periods of high discharge at the Nathrop and Salida sites correspond to the lowest reliability in the power functions. Discharge from Nathrop to Salida during the irrigation season usually decreases due to irrigation withdrawals and the lack perennial tributaries. Load flux in this reach exhibits little increase and some decrease during the highest flows.

Chapter 3

Lower Arkansas River Basin Investigations

3.1 Lower Arkansas River Basin (LARB) Study Regions

Colorado's Lower Arkansas River Basin (LARB) begins at the outlet of the river from Pueblo Reservoir and extends eastward across the High Plains to the border with Kansas. The alluvial valley of the Arkansas River in the LARB, the focus of the current studies, supports one of Colorado's most important agricultural areas, forming the economic backbone of small cities like La Junta and Lamar along with numerous small towns and communities.

The studies reported herein are conducted in two representative regions within the alluvial valley, one upstream of John Martin Reservoir and the other downstream (Figure 3.1). The Upstream Study Region (USR) extends along a 48.5-mi reach of the river from just west of the town of Manzanola to Adobe Creek and encompasses a total of about 125,000 ac, of which about 65,200 ac are irrigated. Stretching about 44.1 mi along the river from the May Valley Drain at Lamar to the Colorado-Kansas border, the Downstream Study Region (DSR) covers about 136,300 ac, with about 81,500 ac irrigated.

Flow rates in the Arkansas River and in major tributaries in the LARB and flow diversions to canals are fairly well gaged and reported by the CDWR and USGS. Thus, records from these gages are relied upon for flow characterization, and the studies reported herein include only limited volumetric flow measurement. Instead, the studies focus on groundwater levels and on surface and groundwater quality. Data on irrigation practices and characteristics and their impacts on crops are reported extensively elsewhere (Gates et al. 2012) and only alluded to in relation to considered hydrological and water quality features of the LARB.

3.1.1 Geologic Setting of the LARB Study Regions

The LARB alluvial valley is broad and thin and is made up of a series of sedimentary formations that are of late Cambrian to Tertiary age (Darton 1906). Marine-derived shale (Pierre, Niobrara, Carlisle, and Graneros) and limestone form the bedrock beneath the majority of the unconfined aquifer with surface outcrops of shale in many locations, but Dakota sandstone underlies the alluvium near the Colorado-Kansas border (Moore and Wood 1967). Evidence indicates that these rocks and their weathered residuum yield a variety of salts, Se, and U under the dissolving action of natural and irrigation flows (Zielinski et al 1995, 1997; Gates et al 2009, Bailey et al 2012). Geological maps (Sharps 1976, Scott 1968) of the LARB may be found online at the National Geologic Map Database (USGS 2013a, b). The alluvial aquifer has a strong hydraulic connection with the Arkansas River and its tributaries (Konikow and Bredehoeft 1974, Person and Konikow 1986).

3.1.2 Hydrologic Setting of the LARB Study Regions

Volumetric rates of flow in the Arkansas River below Pueblo Dam are influenced primarily by patterns of snowmelt and runoff in the UARB, by contributions of groundwater base flow and runoff from precipitation events on the eastern plains, and by the operational rules that govern releases from Pueblo Dam and from John Martin Dam downstream. Average annual precipitation within the alluvial valley increases eastwardly from about 11.2 in just below Pueblo Reservoir, to

11.5 in at La Junta in the USR, and to 15.2 in at Lamar in the DSR. Using data over the period 1992 – 2008 from CoAgMet weather stations, Clifford and Doesken (2009) report average reference ET of about 4.25 ft in the alluvial valley during the irrigation season (15 March – 15 November).

Four stream gages (ARKCATCO, ARKROCCO, ARKLAJCO, and ARKLASCO) are located on the main stem of the Arkansas River in the vicinity of the USR and three (ARKLAMCO, ARKGRACO, and ARKCOOKS) in the vicinity of the DSR (Figure 3.1). Hydrographs of river flow at the gages in the USR are shown in Figure 3.2 over the period of the studies reported herein. Also depicted in Figure 3.2 are plots of normalized flow at these gages over the same period. Normalized flows were computed by dividing the average flow rate during a given day by the long-term average computed over the years 1975 – 2012 for that same calendar date. Normalized flow values above or below 1.0 indicate whether the flow is above or below the long-term average for that date. Similar plots of river gage hydrographs in the DSR are given in Figure 3.3. Normalized flow values averaged over the entire year and across all river stream gages ranged from as low as 0.25 in 2002 to as high as 1.83 in 1999 for the study period in the USR. The values for the DSR study period ranged from 0.20 in 2003 to 0.72 in 2007. Generally, Arkansas River flows at gages were about 23% below the long term average (1975 – 2012) for the 1999 – 2012 study period in the USR and about 53% below for the 2002 – 2012 study period in the DSR. Hydrographs for gages in some of the USR tributary streams, namely Timpas Creek (TIMSWICO), Crooked Arroyo (CANSWKCO), and Horse Creek (HRC194CO), are shown in Figure 3.4. Similar plots are shown for gages in two DSR tributaries, Big Sandy Creek (BIGLAMCO) and Wild Horse Creek (WILDHOCO), in Figure 3.5.

3.1.3 Anthropogenic Factors for the LARB Study Regions

Water required for crop production in the alluvial valley of the LARB substantially exceeds the average annual precipitation of about 1 ft. Thus, a vast irrigation system, originated in the 1870s (Sherow 1990), conveys water to crops along more than 1000 mi within 25 main canals that divert water from the Arkansas River, along with about 2,400 pumping wells. It has been estimated that Colorado water rights for irrigation, including both native and trans-basin water, exceed annual native river flow in the LARB by as much as 40% in a low-flow year (Cain 1985, Sutherland and Knapp 1988). This water deficit is made up by releases from Pueblo and John Martin Reservoirs (Figure 3.1), which store water during the winter period (15 November – 14 March of following year). Trans-basin water is imported to the Arkansas River in the LARB by the Fryingpan-Arkansas Project in an average annual amount of about 57,400 ac-ft. This surplus water from the Fryingpan River and other tributaries of the Roaring Fork River located on the western slope of the Rocky Mountains is delivered both to municipalities and agriculture along the valley of the LARB and is managed by the United States Bureau of Reclamation (USBR) and administered by the Southeastern Colorado Water Conservancy District (SECWCD). In the LARB, a number of smaller off-stream reservoirs are used by canal companies to exchange flow and storage at approved times during the year.

The stream-aquifer system of the valley in the LARB supplies water to municipalities and industry primarily through wells that pump from the alluvium. Treated wastewater is returned either directly to the river or in groundwater seepage from containment and treatment lagoons. These flows, however, are small compared to those exchanged with the river system to and from irrigated agriculture in the valley. Currently, there are a total of about 270,000 irrigated acres in the valley of the LARB, distributed over about 14,000 fields. Major crops in order of cropped area are alfalfa, corn, grass hay, wheat, sorghum, dry beans, cantaloupe, watermelon, and onions (USDA NASS Colorado Field Office 2009). The vast majority of fields are irrigated using surface-irrigation methods with less than about 5% irrigated with sprinklers (typically center-pivot) or drip lines. Application efficiencies of surface and sprinkler irrigation systems were reported by Gates et al. (2012) to average about 72% and 83%, respectively, in the USR and 65% and 88% in the DSR.

Recent available historic flow diversion records from the river into major irrigation canals within the USR are depicted in Figure 3.6 over the period of the studies reported on herein. Also shown in Figure 3.6 are plots of normalized flow at these gages over the same period. Consistent and reliable data on diversions are available back to 1985; thus, normalized flows were computed by dividing the average diverted flow rate over a given day by the long-term average for that same day computed over the years 1985 – 2012. Similar plots of flows diverted to canals in the DSR are given in Figure 3.7. Flow diversions to canals in the USR over the 1999 – 2012 study period were about 11% below the long term average (1985 – 2012). In the DSR, flow diversions to canals were about 16% below the long-term average for the 2002 – 2012 study period.

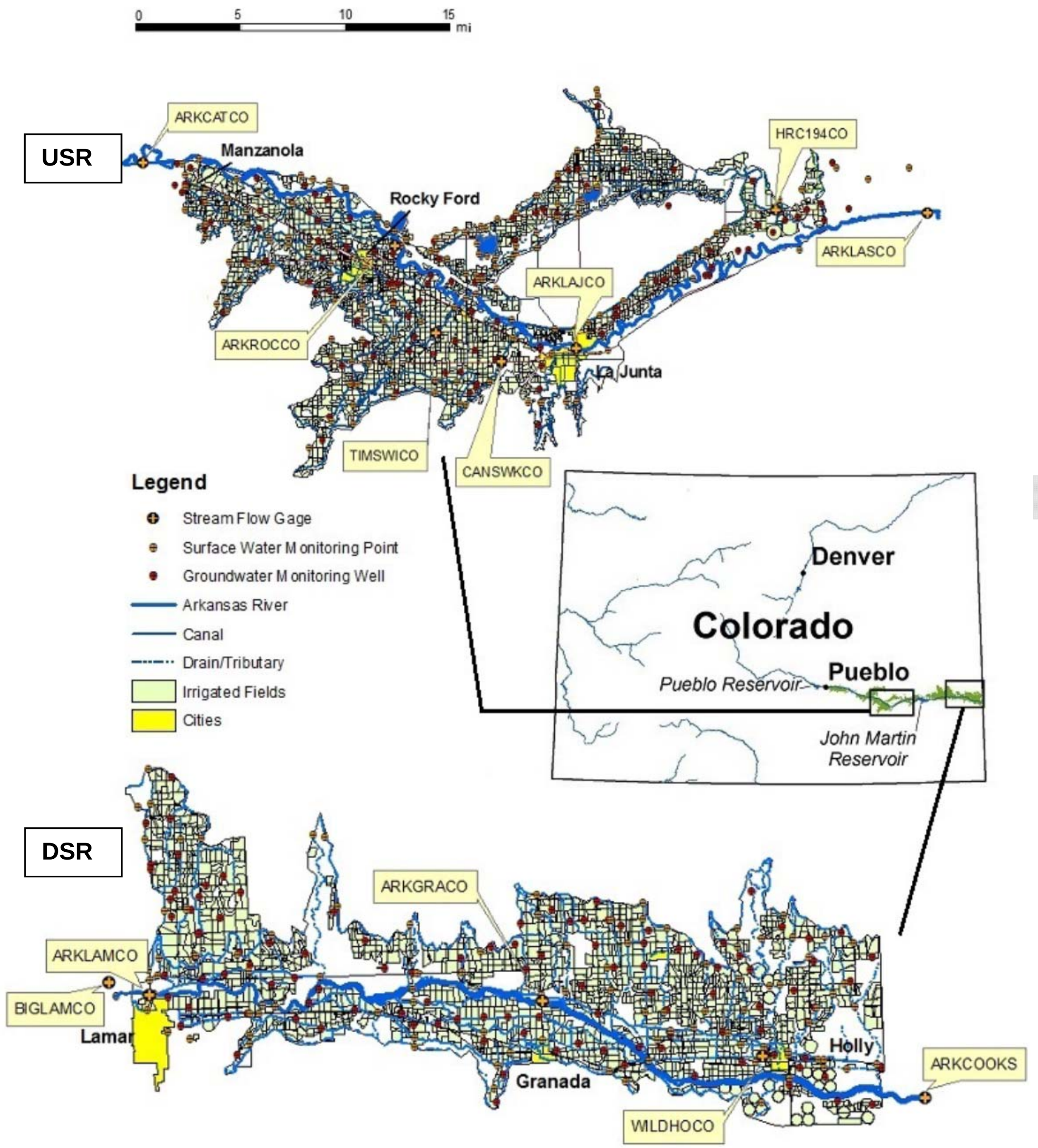


Figure 3.1. The upstream study region (USR) and downstream study region (DSR) in the alluvial valley of the LARB, showing locations of streamflow gages, surface water monitoring sites, and groundwater monitoring wells.

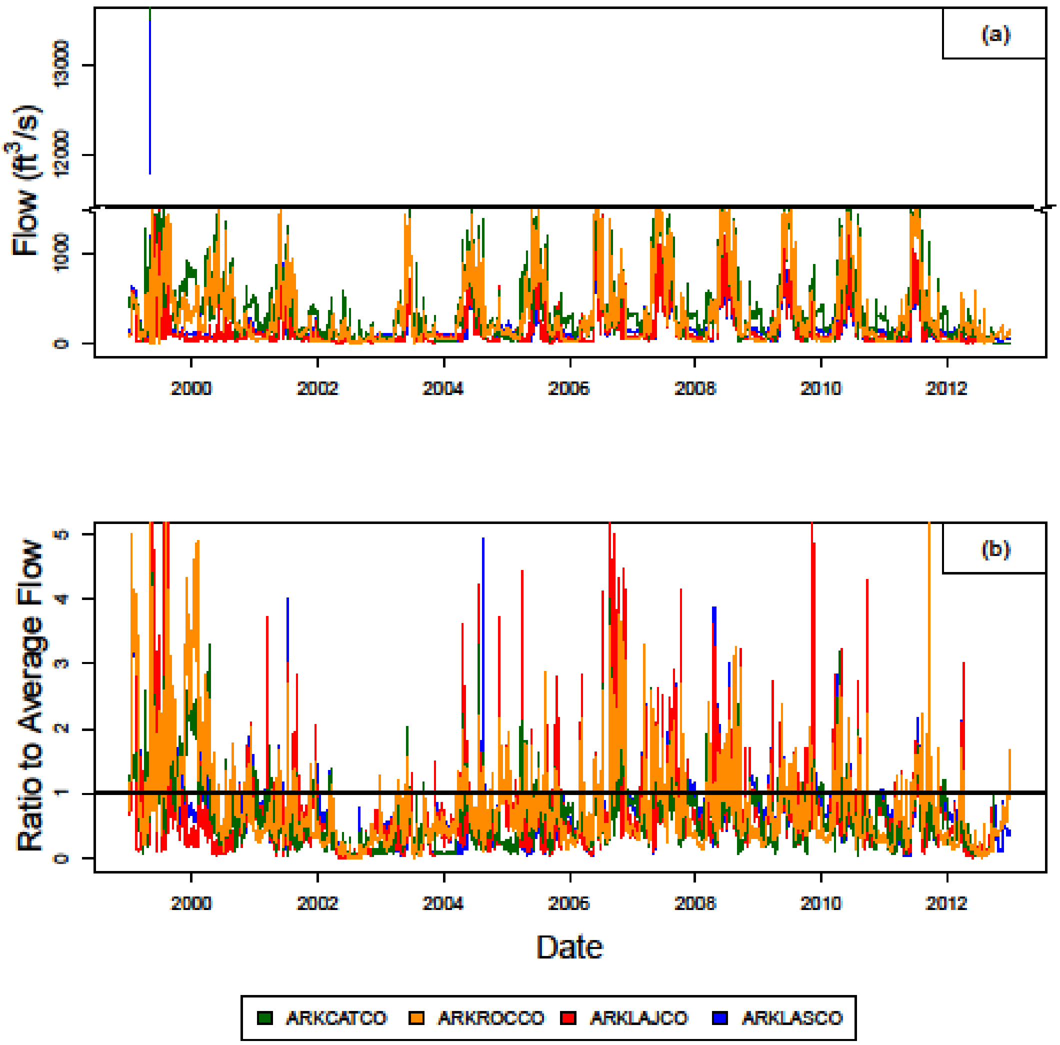


Figure 3.2. Hydrographs of (a) actual and (b) normalized flow at stream gages in the Arkansas River in the vicinity of the USR.

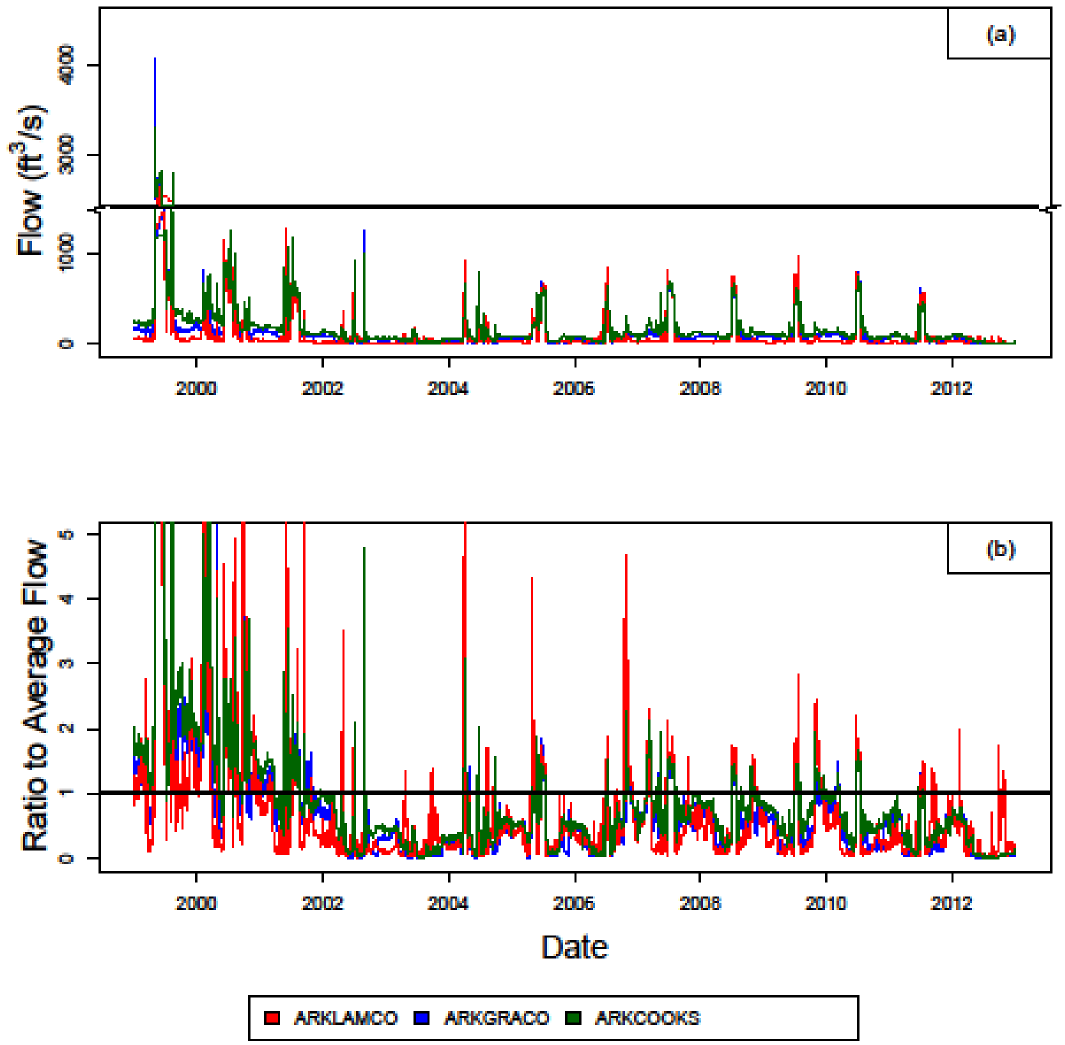


Figure 3.3. Hydrographs of (a) actual and (b) normalized flow at stream gages in the Arkansas River in the vicinity of the DSR.

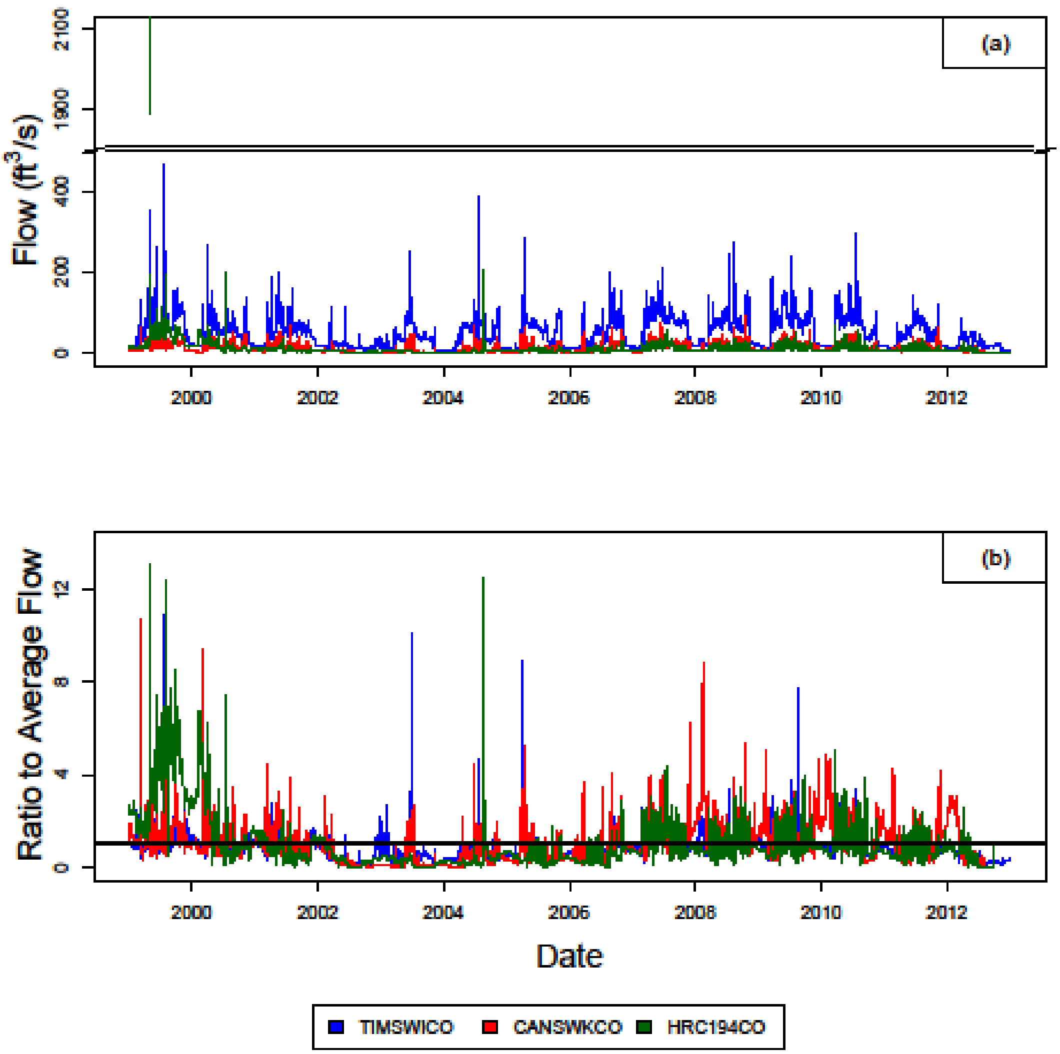


Figure 3.4. Hydrographs of (a) actual and (b) normalized flow at stream gages in the tributaries of the Arkansas River in the vicinity of the USR.

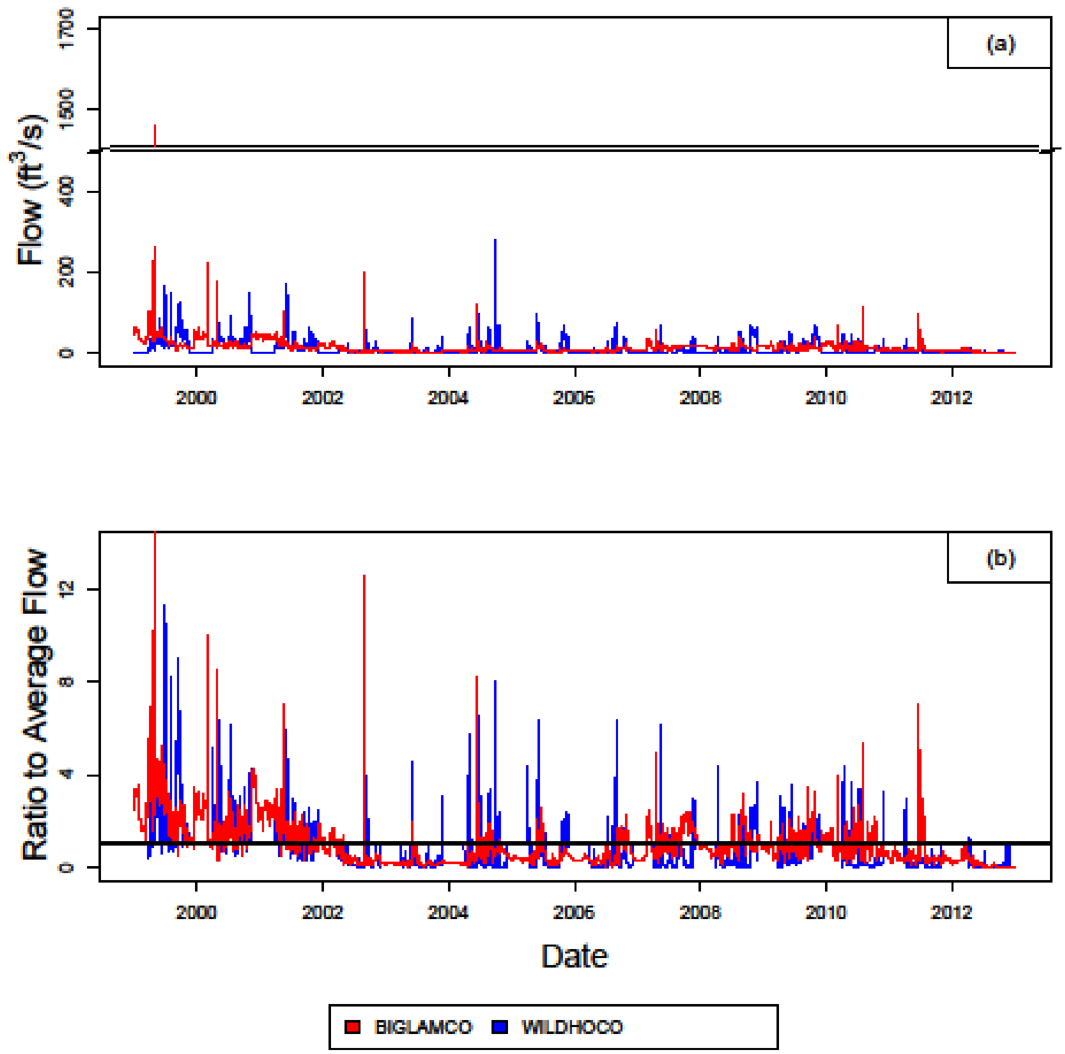


Figure 3.5. Hydrographs of (a) actual and (b) normalized flow at stream gages in the tributaries of the Arkansas River in the vicinity of the DSR.

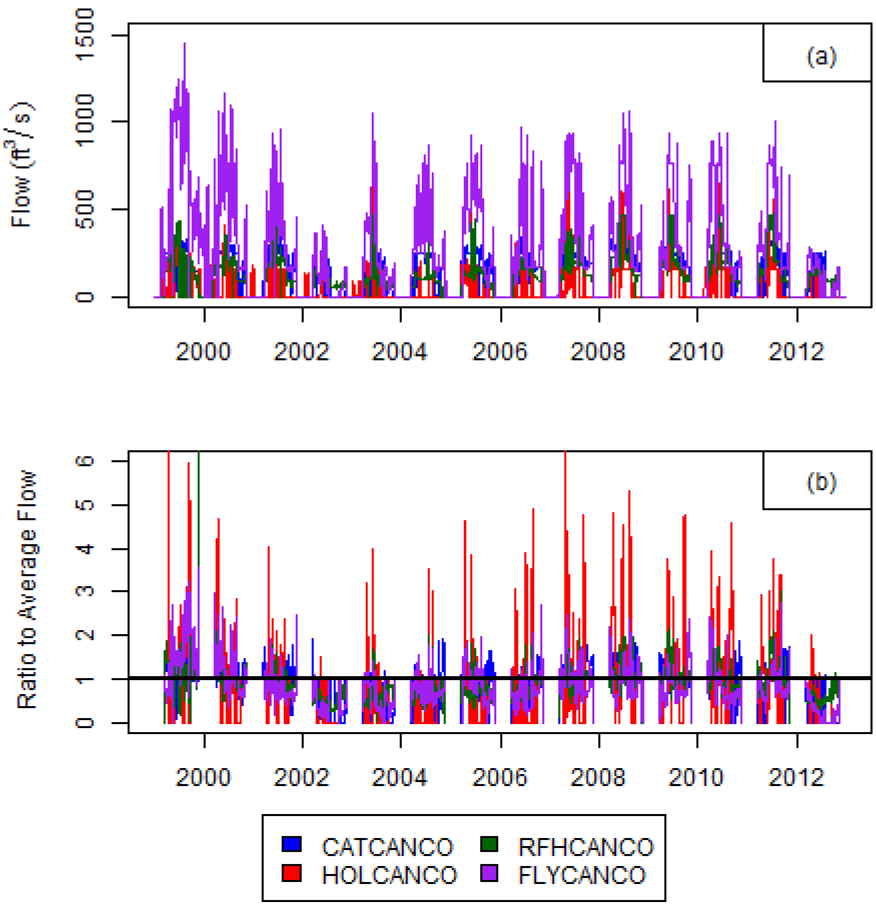


Figure 3.6. Hydrographs of (a) actual and (b) normalized flow diverted from the Arkansas River through canal headgates in the USR.

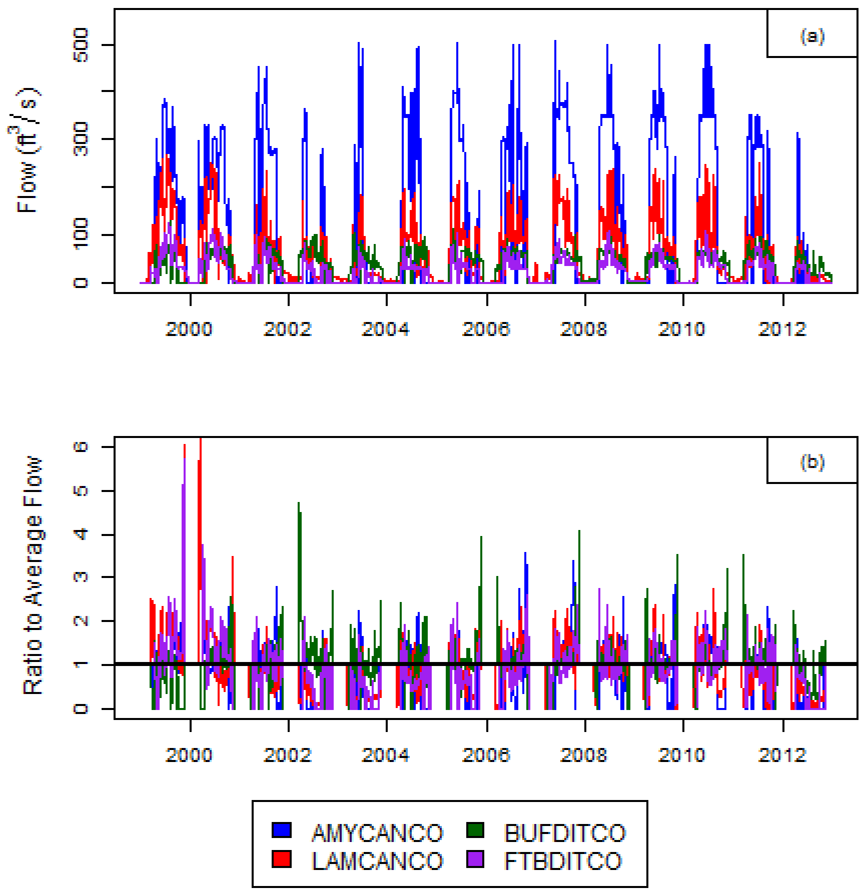


Figure 3.7. Hydrographs of (a) actual and (b) normalized flow diverted from the Arkansas River through canal headgates in the DSR.

Groundwater interaction with the Arkansas River and its tributaries is greatly influenced by irrigation practices in the alluvial valley of the LARB. Irrigation water that is applied to the land in excess of what is required for crop ET percolates below the root zone and much of it makes its way to the underlying groundwater table. Because the water table generally is at a higher elevation than the water levels in the river and tributaries, subsurface water eventually flows back to the streams. Water balance calculations on the river system using available flow data allow estimation of groundwater return flow. Results of such calculations are shown in Figure 3.8 for the reach of the Arkansas River in the USR for April 1999 – October 2007 and in the DSR for April 2002 – October 2007 (Morway et al 2013). Estimated groundwater return flow displays both seasonal and annual variability, occasionally taking negative values, which indicate a net loss from the river due to the effects of groundwater pumping from the alluvial aquifer. Over the analyzed period, average groundwater return to the river reaches was equivalent to about 38.5 ac·ft/wk (2.8 ft^3/s) per mile along the river during the irrigation season and 11.4 ac·ft/wk (0.8 ft^3/s) per mile during the non-irrigation season in the USR. In the DSR, the average irrigation season and non-irrigation season groundwater return flow rates were 19.5 ac·ft/wk (1.4 ft^3/s) per mile and 16.2 ac·ft/wk (1.2 ft^3/s) per mile, respectively.

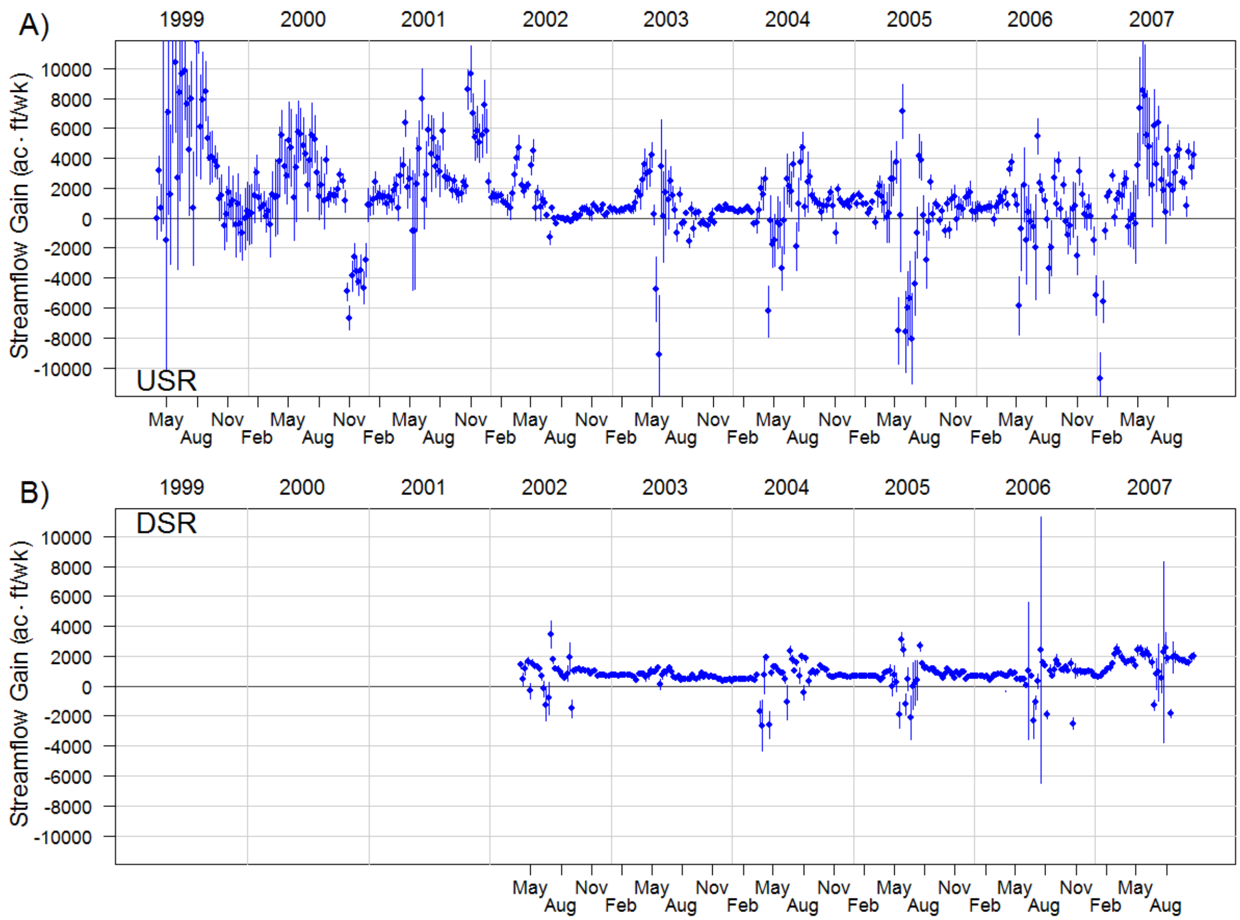


Figure 3.8. Weekly groundwater return flow to the Arkansas River within (A) the USR and (B) the DSR estimated from river water balance calculations (after Morway et al 2013). The points indicate the mean estimated values and the bars indicate the 95th inter-percentile range (between the 2.5th percentile and 97.5th percentile).

The Arkansas River Compact with Kansas constrains the operation of irrigation systems in the valley of the LARB by prohibiting any changes to the system that would alter the return flow patterns (amount, spatial pattern, and timing) so as to cause the flow in the Arkansas River to be "materially depleted in usable quantity or availability for use to the water users in Colorado and Kansas" (Colorado Revised Statues 1949). Hence, reductions in excess surface or subsurface flows that result from amendments to water management practices, such as reductions in irrigation water application or increased well pumping, are prohibited unless otherwise augmented to offset diminished return flows to the river.

3.2 Methodology of Data Collection in the LARB Study Regions

3.2.1 Surface Water Monitoring Sites and Schedule in the LARB Study Regions

The CWCB and ABR project provided for limited flow measurement in four small ungauged tributaries to the Arkansas River. Also, canal seepage tests were conducted in three canals and compared to findings from previous tests conducted by CSU, which are reported elsewhere.

Numerous sites were chosen along the main stem of the Arkansas River, tributary streams and open collector drains, and canals to monitor surface water quality within the USR and DSR. The sample locations are depicted in Figure 3.1. These locations consist of 11 and 8 sites along the Arkansas River in the USR and DSR, respectively; 54 and 81 sites in tributaries and drains in the USR and DSR, respectively; and 110 and 34 sites in irrigation canals in the USR and DSR, respectively. A detailed list of the surface water monitoring sites in the USR and DSR, along with their approximate GPS coordinates, is given in Table A3.1 on the ARBhwq CD.

From 1999 – 2012 in the USR and 2002 – 2012 in the DSR, periodic in-situ measurements of selected water quality characteristics were made at surface water monitoring sites. Beginning in 2006 in the USR and in 2003 in the DSR, water samples were gathered from many of these locations for laboratory analysis of dissolved constituent concentrations. Prior to these dates, water samples were gathered on an aperiodic schedule and analyzed from a small number of locations. The number of sites in surface water bodies at which in-situ measurements and water samples were routinely sampled and the frequency of sampling have been reduced over the years due to funding limitations.

3.2.2 Groundwater Monitoring Sites in the LARB Study Regions

A total of about 106 observation wells in the USR and 120 wells in the DSR have been used to monitor water table levels and aquifer water quality over the study period. Monitoring well locations are shown in Figure 3.1. Initially, well locations were selected using a form of stratified random sampling (Gilbert 1987) to prevent bias in their placement. Adjustments were made to comply with landowner permission and preferences. Later, more wells were added to fill in data gaps in the study regions. Typically, a single monitoring well was placed within a managed field unit. To gain insight into field-scale variability of groundwater tables and water quality, several fields were selected for installation of multiple wells. Results and analysis of in-field variability are discussed in Gates et al (2012) and Morway et al (2013). A list of the groundwater monitoring well sites in the USR and DSR and their approximate GPS coordinates are given in Table A3.2 on the ARBhwq CD.

3.2.3 Surface Water Measurements in the LARB Study Regions

3.2.3.1 In-Situ Monitoring of Surface Water in the LARB Study Regions

From 1999 to 2006 in the USR and from 2002 to 2003 in the DSR, in-situ measurements at surface water monitoring sites consisted of EC (measured as specific conductance at 25^{o}C) and *T*. Handheld conductivity meters (typically YSI 30^{TM} model) were used with the probe placed in the flowing stream at a location near the midpoint of the channel cross-section at the monitoring site. Measurements at multiple locations within river cross-sections revealed negligible differences (typically less than 2%), leading to the conclusion that a single measurement located midstream within each cross section would be sufficient. In 2006 in the USR and in 2003 in the DSR, in-situ measurements were expanded to include pH, DO, and ORP at selected locations. In 2009, measurement of these parameters was extended to all surface water monitoring sites. YSI 600QS ^{TM} multiprobe devices were used to gather these data. In total, over the period June 1999 – August

2012, 18,410 in-situ measurements were taken during 215 sampling events at surface water locations in the USR. From April 2002 to August 2012, 14,161 in-situ measurements were taken during 173 sampling events at surface water locations in the DSR.

Handheld conductivity meters were calibrated for EC at least once daily in the field using a standard solution, typically with EC = 1.4088 dS/m (potassium chloride). The YSI 600QS ™ multiprobe was calibrated for use in the field following YSI recommendations and guidelines, as described in Section *2.2.3.1.1*.

3.2.3.2 Surface Water Quality Sampling in the LARB Study Regions

From June 2006 to January 2012 in the USR and from June 2003 to August 2012 in the DSR, surface water samples were gathered routinely at a subset of tributary and river sites for laboratory analysis of several dissolved constituents of interest. A total of 269 samples were gathered during 19 sampling events in the USR and 755 samples over 49 events in the DSR. Water samples typically were not gathered from irrigation canal sites. Samples were gathered, stored, transported, and analyzed using the protocols described in Section *2.2.3.1.2*. Laboratory analysis of the water samples yielded estimates of pH, sodium adsorption ratio (SAR), EC, and dissolved concentrations of Na, Ca, K, Mg, NO_3, SO_4, Cl, CO_3, HCO_3, B, Se, and U. An estimate of total dissolved solids (TDS) was made by summing the concentrations of the analyzed dissolved ions. During a few sampling events, samples for dissolved Pb, total recoverable Se, total recoverable Fe, selenite (SeO_3), Mn, and gaseous P also were gathered and analyzed. In gathering samples for analysis of total recoverable Se and total recoverable Fe, filters were not used on the sampling tubes to permit particulate forms of the elements to be retained in the samples. A summary of the dates and extent of sampling events is provided in Tables A3.3 and A3.4 for the USR and DSR, respectively, on the ARBhwq CD.

3.2.3.3 Irrigation Canal Seepage Testing in the LARB Study Regions

From 2001 to 2007, flowing water balance (inflow-outflow) seepage tests were conducted on three canals in the USR and three canals in the DSR. Tests were conducted on one additional canal located in a nearby region just east of the USR. Estimated seepage rates ranged from 0.0 to 3.2 ft^3/s per mile in canals in the USR and from 0.0 to 6.6 ft^3/s per mile in the DSR. Methodology and results for most of these tests are described in detail in Susfalk et al (2008), Martin (2014), and Martin and Gates (2014). In the present report, inflow-outflow tests carried out in 2011 on the Fort Lyon Canal, the Rocky Ford Highline Canal, and the Lamar Canal under funding from CWCB and the ABR, are described.

Six inflow-outflow tests were conducted on three different reaches along the Fort Lyon Canal on 12 – 14 July 2011. The locations of the reaches are depicted on Figure 3.8. Reach 1 extended about 12.5 mi along the canal from the bridge crossing of Bent County Road 7 to the bridge crossing of Bent County Road 17. Reach 2 was about 11 mi in length and stretched from Bent County Road 17 to a cross-section approximately 1.8 mi upstream of the bridge crossing of Bent County Road 24. Reach 3 encompassed the combination of both Reaches 1 and 2, extending for a total of about 23.5 mi. Two inflow-outflow tests were conducted on Reach 1, two on Reach 2, and two on Reach 3.

Four tests were conducted on 11 August 2011 on a single 7.3-mi reach of the Rocky Ford Highline Canal (Figure 3.9). This reach extended from the bridge crossing of Otero County Road 9 to a cross section about 1.7 mi downstream of the bridge crossing of Otero County Road 12.

On the Lamar Canal, four tests were conducted on 12 August 2011 on a single 9-mi reach (Figure 3.10). This reach stretched from just east of the bridge crossing of Prowers County Road 14 to about 2.9 mi downstream of the bridge crossing County Road 19 (just upstream of "Seven Falls").

Canal flow rates were measured simultaneously at the upstream and downstream end of the test reaches of the Fort Lyon canal using acoustic Doppler current profilers (ADCP) tethered to small boats (Figure 3.11) (Oberg et al 2005, Mueller and Wagner 2009). Pressure transducers were installed in the canal at the upstream and downstream ends of the test reach and at about every 2 mi along the reach for use in determining water level fluctuations and for estimating canal wetted-perimeter area. The transducer model used was the *Onset HOBO U20 Water Level Data Logger*^{TM}. Pressure measurements were taken every 1 min for estimating the canal water level just prior to and during the test. An additional pressure transducer was deployed in the vicinity of the test reach as a barometric pressure logger for stage measurement corrections. A tape was used to measure the water surface width at the location of each pressure transducer and at intermediate locations mid-way between each pressure transducer. Also, the approximate slopes of the canal banks at the water surface were determined at these locations. Weather data from the CoAgMet weather station Lamar No. 4 (located about 4.5 mi north northeast of the city of Lamar) were used to compute estimated evaporation rates from the canal water surface during the tests.

Like the seepage tests on the Fort Lyon canal, simultaneous flow rate measurements were made with ADCPs at the upstream and downstream ends of the test reaches on both the Rocky Ford Highline Canal and the Lamar Canal. Depth from the water surface to the channel bed was measured at 30 to 40 locations from the left channel bank to the right channel bank to define cross-section geometry at one mile intervals along the test reaches of both canals. Pressure transducers also were installed at 1 mi intervals along the reaches to estimate changes in water level during the tests. A tape was used to measure the water surface width at intervals of about 0.5 mi along the test reaches of each canal.

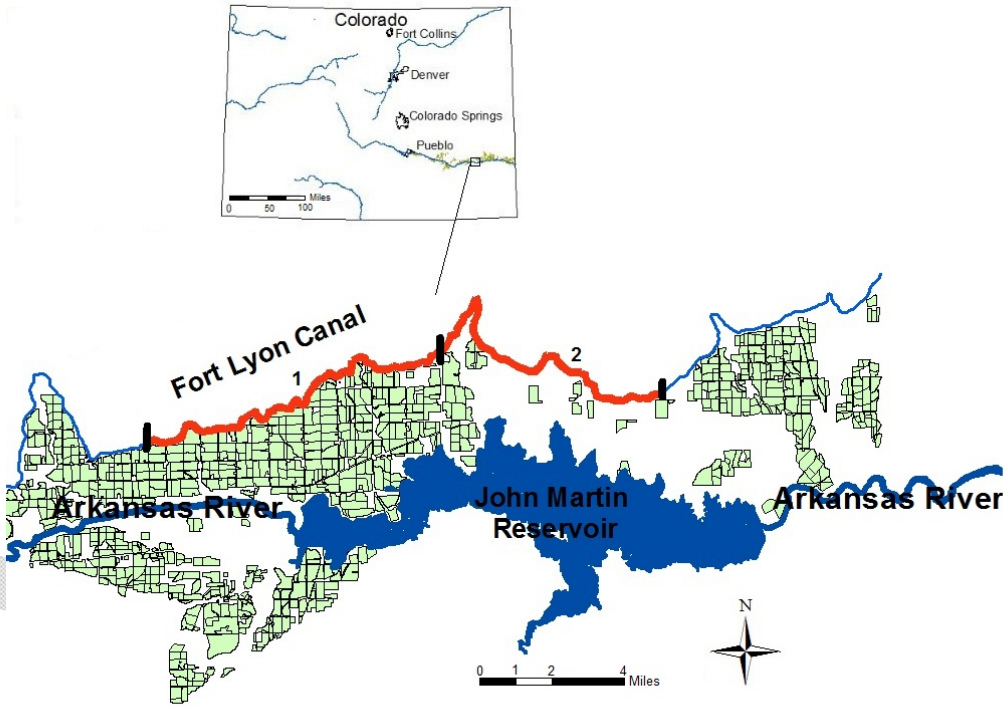


Figure 3.8. Location of Reaches 1 and 2 on the Fort Lyon Canal for seepage tests in July 2011 (red portion of canal). Reach 3 is defined as the combination of Reaches 1 and 2.

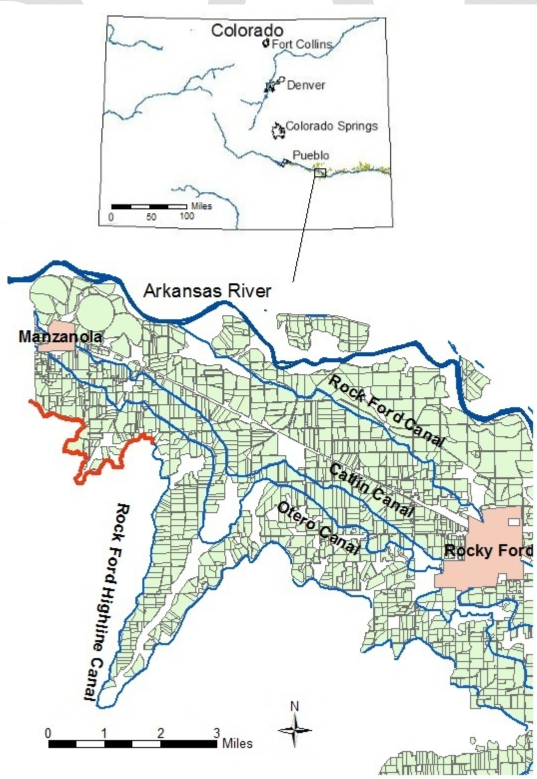


Figure 3.9. Location of the reach on the Rocky Ford Highline Canal for seepage tests in August 2011 (red portion of canal).

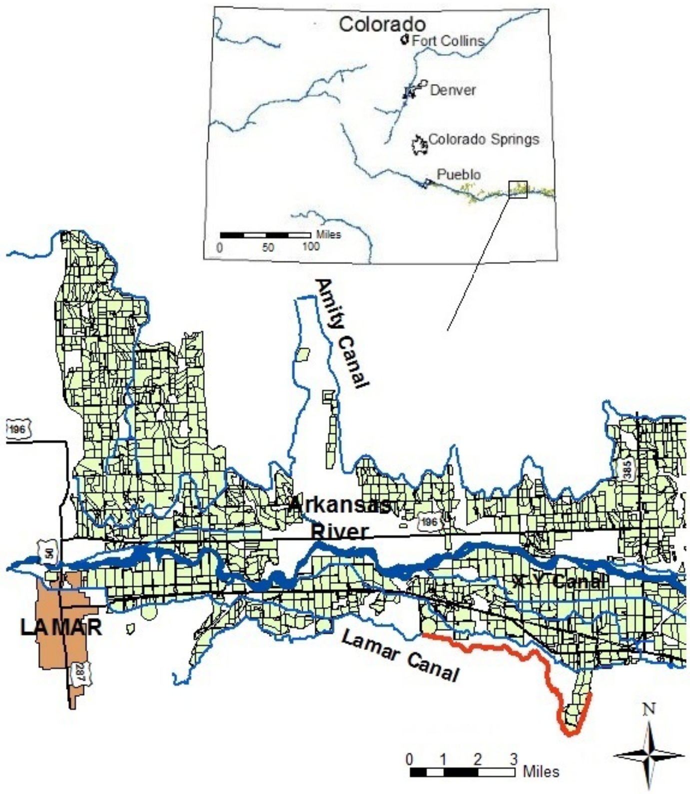


Figure 3.10. Location of the reach on the Lamar Canal for seepage tests in August 2011 (red portion of canal).

Figure 3.11. Using an ADCP to measure flow rate through a cross section on the Fort Lyon Canal in July 2011, with a close-up of the ADCP shown.

3.2.3.4 Flow Measurements in Selected Ungaged Tributaries in the DSR

Streamflow rates were measured on three occasions between August 2010 and May 2011, coincident with collection of water quality samples, from four small tributary streams without permanent stream gaging stations in the DSR. The aim was to gain a better understanding of the order of magnitude of typical flows and solute mass loads in these streams. A SonTek FlowTracker™ Handheld Acoustic Doppler Velocimeter (ADV) was used for all measurements following procedures described in Section 2.2.3.1.1 of this report.

Flow in the May Valley Drain was measured immediately upstream of Colorado Highway 196, north of Lamar. This channel has a highly irregular path and cross-section. The channel bed is very silty and moderately vegetated throughout the year. The banks are steep and heavily vegetated. Downstream of this gaging location, the May Valley Drain enters private property, and access to this property to allow flow gauging further downstream was not available. The available site for measurements was not ideal for performing stream gaging; it is estimated that measurements may be off by ±15% due to the highly-variable velocity profile encountered.

Clay Creek was gaged just before it discharges into the Arkansas River, approximately 0.25 mi downstream of US Highway 50, east of Lamar. This channel has a fairly straight path and relatively uniform cross-section along the gaged reach. The bed is sandy and relatively clear of vegetation, and the banks have shallow slopes and are lightly to moderately vegetated. Gaging and water quality sampling was conducted upstream of a fence crossing the stream.

Buffalo Creek was gaged immediately upstream of Prowers County Road JJ, north of Granada. This channel has a fairly straight path and constant-cross section along the gaged reach. The bed is silty to sandy and is moderately vegetated for portions of year. The channel banks have mild slopes and are moderately vegetated.

Flow in the Holly Drain was measured upstream of an abandoned Burlington Northern and Santa Fe railroad bridge, south of US Highway 50, and west of Holly. This man-made channel is very straight with a uniform cross-section. The bed is silty and lightly vegetated for portions of the year, with steep banks that are moderately vegetated.

3.2.4 Groundwater Measurements in the LARB Study Regions

Groundwater monitoring wells in the LARB consist of a 2.5-in diameter PVC pipe with slot width of 0.015 in over the entire length of the PVC pipe below the water table, yielding a slotted density of 0.02 ft^2 per lineal ft. The PVC pipes were inserted into holes drilled with an auger using a truck-mounted Giddings™ drill rig. After placement of the pipe, the annulus around the pipe at the ground surface was packed with moistened bentonite to inhibit entry of surface water. Monitoring wells were capped on the top between readings. Depth of the monitoring wells varied from 5 ft to 39 ft, averaging 13.9 ft, in the USR and 8.2 ft to 27.5 ft, averaging 16.2 ft, in the DSR. Groundwater monitoring wells periodically were purged of silt (typically once or twice annually) using submersible pumps to insure good hydraulic connection of the water level in the well with that in the surrounding aquifer. Each well periodically was repacked with bentonite clay around the annulus to preserve the surface seal. Many wells had to be repaired or replaced several times over the course of the studies due to damage from agricultural field operations.

Over the period April 1999 – August 2012, a total of 19,497 groundwater table and in-situ water quality measurements were made in groundwater monitoring wells during 219 sampling events in the USR. From April 2002 to August 2012, a total of 19,192 groundwater table and in-situ measurements were made in groundwater monitoring wells during 179 sampling events in the

DSR. Beginning in 2006 in the USR and in 2003 in the DSR, water samples were collected routinely from a larger number of wells for laboratory analysis of dissolved constituents.

3.2.4.1 Measurement of Groundwater Levels in the LARB Study Regions

The water table level in monitoring wells in the LARB typically was measured using an open-spool tape with a small weight and a calibrated Styrofoam float attached to the end of the tape. The distance from the top of the well casing to the water table was recorded along with the distance from the ground surface to the top of the well casing at the measurement point (Figure 3.12). The difference between these two distances was taken as the water table depth, D_{wt}, from ground surface. From 2006 to 2011 in the USR and 2003 – 2011 in the DSR, electronic sounding tapes, in addition to the tapes with floats, occasionally were used to measure distance to the water table from the top of the well casing.

Figure 3.12. Measuring depth to water table in a groundwater monitoring well in the DSR using an open-spool tape.

3.2.4.2 In-Situ Monitoring of Groundwater Quality in the LARB Study Regions

From 1999 to 2006 in the USR and from 2002 to 2003 in the DSR, measurements of groundwater EC and *T* were made using handheld conductivity meters, typically a YSI 30™ model. Each meter was calibrated with a standardized saline solution at least once daily during each sampling period. The probe was lowered into the monitoring well and readings were taken near the water table, near the bottom of the well, and approximately midway between the water table and the bottom of the well. The averages of these readings were taken as the average EC and *T* in the well. The probe was rinsed with de-ionized water after each reading. In 2006 in the USR and in 2003 in the DSR, pH, DO, and ORP were added to in-situ measurements for a subset of the monitoring wells. In 2009, measurement of these parameters was extended to all groundwater monitoring wells.

The EC reading taken midway between the groundwater table and the bottom of the well typically was within 2% of the average of the three readings along the water column. Thus, to save time and reduce cost, beginning 21 July 2009, readings of EC, *T*, pH, DO, and ORP were taken only at a single point located at approximately midway between the water table and the bottom of the monitoring well using a YSI 600QS™ multiprobe. The multiprobe was calibrated following YSI recommendations and guidelines, as described in Section *2.2.3.1.1* of this report.

3.2.4.3 Groundwater Quality Sampling in the LARB Study Regions

The techniques for low-flow sampling, storage, and transportation to the laboratory (described in Section *2.2.3.2.2*) were followed in collecting filtered water samples from a subset of groundwater monitoring wells in the USR from 2006 to 2011 and in the DSR from 2003 to 2011 (Figure 3.13). Samples routinely were analyzed for Na, Ca, K, Mg, NO_3, SO_4, Cl, CO_3, HCO_3, B, Se, and U. During a few sampling events, samples for dissolved Fe, Pb, SeO_3, Mn, nitrite (NO_2), orthophosphate (PO_4), and total recoverable Se and Fe also were gathered and analyzed.

Figure 3.13. Collecting a filtered water quality sample from a groundwater monitoring well in the USR using a low-flow bladder pump.

3.3 Data Analysis and Results in the LARB Study Regions

3.3.1 Surface Water Quantity in the LARB Study Regions

3.3.1.2 Surface Water Flow Rates in the LARB Study Regions

Flow rates measured using ADVs in the May Valley Drain, Clay Creek, Buffalo Creek, and the Holly Drain in the DSR in 2010 – 2011 are summarized in Tables 3.1 – 3.4. Though limited, the data provide an indication of the order of magnitude of flow rates in these small ungaged waterways that contribute to the Arkansas River. The sum of these flows is equivalent to about 10% to 40% of average gaged flow in the Arkansas River in the USR.

Table 3.1. Flow and estimated constituent mass discharge from May Valley Drain to the Arkansas River.

Date	Flow (ft^3/s)	Mass Flux Rate (lb/day)			
		U	Se	NO_3-N	SO_4-S
Aug-10	13.9	5.9	1.8	269	38543
Nov-10	4.8	2.7	0.8	99	14811
May-11	3.8	1.7	0.7	44	11212

Table 3.2. Flow and estimated constituent mass discharge from Clay Creek to the Arkansas River.

Date	Flow (ft^3/s)	Mass Flux Rate (lb/day)			
		U	Se	NO_3-N	SO_4-S
Aug-10	11.2	1.6	0.4	121	29485
Nov-10	3.6	0.7	0.2	22	10661
May-11	3.9	0.6	0.1	13	10057

Table 3.3. Flow and estimated constituent mass discharge from Buffalo Creek to the Arkansas River.

Date	Flow (ft^3/s)	Mass Flux Rate (lb/day)			
		U	Se	NO_3-N	SO_4-S
Aug-10	9.2	3.7	1.7	115	30821
Nov-10	3.4	1.7	0.6	40	12033
May-11	3.0	1.2	0.5	22	9823

Table 3.4. Flow and estimated constituent mass discharge from Holly Drain to the Arkansas River.

Date	Flow (ft^3/s)	Mass Flux Rate (lb/day)			
		U	Se	NO_3-N	SO_4-S
Aug-10	37.1	15.7	4.0	461	136699
Nov-10	27.5	16.8	3.3	386	98211
May-11	27.4	12.0	2.8	236	93862

3.3.1.3 Irrigation Canal Seepage in the LARB Study Regions

Data gathered during the inflow-outflow tests for seepage along reaches of the Fort Lyon Canal, Rocky Ford Highline Canal, and Lamar Canal were analyzed using the water balance analysis described in Section *2.3.1.2*. Only one of the six seepage tests conducted on the Fort Lyon Canal yielded valid results. For the other five, moving channel bed problems (Oberg et al. 2005, Mueller and Wagner 2009) at the upstream and/or downstream end of the reaches prevented accurate estimates of flow rate using the ADCP data. Similar problems occurred for two of the four tests on the Rocky Ford Highline Canal. However, all four tests on the Lamar Canal provided valid results. The resulting estimates of seepage are summarized in Table 3.5. Martin (2014) and Martin and Gates (2014) reported comparable mean values ranging from -1.14 ft^3/s per mile along the canal [-0.56 ft/day (gain) through the canal wetted perimeter area] to 3.46 ft^3/s per mile [2.26 ft/day], and averaging 1.49 ft^3/s per mile [0.92 ft/day], over 18 different inflow-outflow tests conducted on a 3.7-mi reach of the Rocky Ford Highline Canal located several miles upstream of the test reach reported here. For 15 tests conducted along a 2.4-mi reach of the Catlin Canal in the USR, Martin (2014) Martin and Gates (2014) reported mean seepage values ranging from 0 to 4.88

ft^3/s per mile [3.1 ft/day], averaging 1.95 ft^3/s per mile [1.25 ft/day]. These losses are substantial, constituting roughly 5% to 25% of the canal flow rate at the upstream end of each test reach.

Table 3.5. Summary of results for inflow-outflow seepage tests on the Fort Lyon, Rocky Ford Highline, and Lamar Canals in Summer 2011.

Canal	Test Number	Test Reach Inflow Rate (ft^3/s)	Test Reach Length (mi)	Seepage		
				ft^3/s per mile	ft/day *	Average % Loss per mile
Fort Lyon	1	574.47	23.5	3.37	0.88	0.59
Rocky Ford Highline	1	133.15	7.3	1.37	0.40	1.03
	2	129.67	7.3	0.84	0.24	0.64
Lamar	1	47.79	9.0	1.29	0.90	2.70
	2	48.19	9.0	1.00	0.70	2.08
	3	50.58	9.0	0.81	0.57	1.61
	4	52.90	9.0	0.73	0.51	1.39

* - (ft^3/day) per ft^2 of channel wetted–perimeter area

3.3.2 Surface Water Quality in the LARB Study Regions

3.3.2.1 In-situ Water Quality Parameters in the Surface Water in the LARB Study Regions

Tables A3.5, A3.6, and A3.7 in Excel File 3A on the ARBhwq CD summarize spatial statistics over all sampled locations in the Arkansas River, tributaries and drains, and canals, respectively for measured values of EC, *T*, pH, DO, and ORP for each sampling event in the USR. Similar summaries are given in Tables A3.8, A3.9, and A3.10 in Excel File 3B on the ARBhwq CD over all sampled locations in the Arkansas River, tributaries and drains, and canals, respectively, for EC, *T*, pH, DO, and ORP for each sampling event in the DSR.

Measured values of EC in the Arkansas River typically are moderate to high, reflecting high concentrations of TDS. Box and whisker plots of temporal statistics of EC for all sample locations along the Arkansas River within the USR for 1999 – 2012 and along the DSR for 2002 – 2012 are shown in Figure 3.13. In the USR, average EC values along the river increase in the downstream direction from about 1 dS/m near Manzanola to about 1.8 dS/m near Las Animas. In the DSR, EC along the river increases in the downstream direction from about 2.2 dS/m just downstream of John Martin Reservoir to about 4 dS/m near the Colorado-Kansas border. Average EC values measured in the tributaries and drains in the USR were about 2.3 times the values measured within the river. In the DSR, however, EC values measured in the tributaries are very similar to those measured in the river. This similarity may be indicative of the fact that a larger fraction of river flow is made up of groundwater return flow in the DSR and that TDS concentrations are approaching or exceeding the limit of chemical saturation for $CaSO_4$ (gypsum). In the USR, the average measured EC in the groundwater was about 2.6 times the average EC values measured in the river and 1.1 times the average EC values in the tributaries; whereas in the DSR, the average groundwater EC was about 1.4 times the average EC measured in the river and that measured in the tributaries.

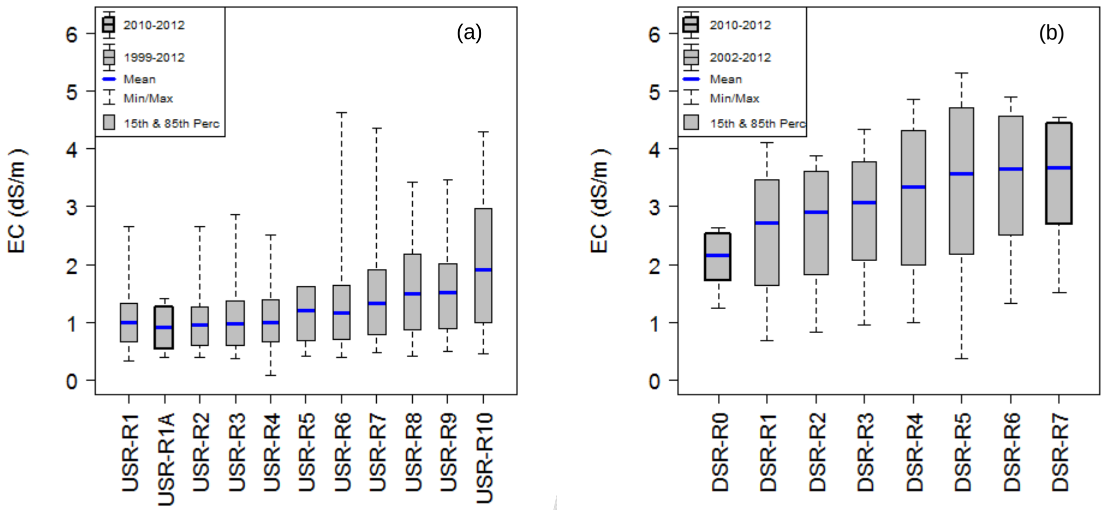


Figure 3.13. Box and whisker plots of EC measured at locations along the Arkansas River in (a) the USR and (b) the DSR.

Ranges of observed values of *T*, pH, DO, and ORP were fairly typical for environmental surface waters in this type of setting and generally comply with Colorado standards and guidelines (CDPHE 2010). Spatial average measured values of pH in the Arkansas River ranged from 7.36 to 8.55, with an overall average across the sampling events of 7.88 in the USR. In the DSR spatial average pH measured in the river ranged from 7.13 to 9.12, with overall average across sampling events of 7.92. Spatial average measured values of DO in the river ranged from 4.34 to 16.13 mg/L, with an overall average across the sampling events of 9.28 mg/L in the USR. Spatial average DO measured in the river in the DSR ranged from 6.59 to 15.65 mg/L, with an overall average across the sampling events of 9.72 mg/L.

3.3.2.2 Dissolved Chemical Concentrations in the Surface Water in the LARB Study Regions

3.3.2.2.1 TDS and Major Salt Ions in the Surface Water in the LARB Study Regions

The spatial statistics of TDS and the concentrations of major salt ions for all sample locations in the Arkansas River, tributaries and drains, and canals are summarized in Tables A3.11, A3.12, and A3.13, respectively, in Excel File 3C on the ARBhwq CD for all sampling events from 2006 to 2011 in the USR and in Tables A3.14, A3.15, and A3.16, respectively, in Excel File 3D for all sampling events from 2003 to 2011 in the DSR. An abridged summary of these data, which presents the number of measurements, average, and CV for each sampling event for TDS in the Arkansas River, is provided in Table 3.6 for the USR and DSR. Abridged statistical summaries for the principal cation concentrations in the river are shown in Tables 3.7 and 3.8 for the USR and DSR, respectively. Tables 3.9 and 3.10 present summaries of the principal anion concentrations in the river for the USR and DSR, respectively.

Shown in Figure 3.14 are box-and-whisker plots of TDS in the USR and DSR. In the USR, average values of TDS along the river increases in the downstream direction from about 750 mg/L near Manzanola to about 1300 mg/L near Las Animas, averaging 930 mg/L along the whole reach. In the DSR, TDS along the river increases in the downstream direction from about 2000 mg/L just downstream of John Martin Reservoir to about 3600 mg/L near the Colorado-Kansas border, averaging 2930 mg/L along the reach. These values pose a high hazard to irrigated crops (Wallender and Tanji 2012) and greatly exceed the 500 mg/L EPA maximum allowable TDS concentration for drinking water (USEPA 2009).

In Figures 3.15 and 3.16 are box-and-whisker plots of the concentrations of principal cations (Ca, Na, and Mg), and the concentrations of principal anions (SO_4, HCO_3, and Cl), respectively, in the USR. These plots reveal the considerable temporal variability over sampling events at sampling locations along the Arkansas River, attributed primarily to variability in river flow rate. Similar plots of predominant cation and anion concentrations are shown in Figures 3.17 and 3.18, respectively, for the DSR.

The average milliequivalent fraction of TDS for principal cations in all surface water samples from the USR is 23% for Ca, 13% for Na, and 13% for Mg. In the DSR the relative fractions are 18% for Ca, 19% for Na, and 14% for Mg. For principal anions in the surface water samples from the USR the average fractions are 35% for SO_4, 11% for HCO_3, and 3% for Cl In the DSR the principal anion fractions are 39% for SO_4, 6% for HCO_3, and 3% for Cl. Thus, the waters of the Arkansas River in the LARB study regions are a Ca/Na- SO_4 type with the Na cation growing in prominence in the downstream direction, perhaps indicative of ion exchange and an exceedance of gypsum solubility.

Table 3.6. Abridged statistical summary of TDS in water samples gathered from the Arkansas River within the USR and DSR.

USR						
Sampling Trip Description (Water Quality Trip)				TDS (mg/L)		
Trip Number	Start Date	End Date	No. Sites Visited	No. Evalu-ations	Average	CV
155 (S1)	6/17/2006	6/20/2006	-	10	420	0.21
168 (S2)	5/21/2007	5/24/2007	-	9	523	0.09
173 (S3)	10/11/2007	10/11/2007	10	10	837	0.13
175 (S4)	3/20/2008	3/22/2008	10	10	1199	0.39
178 (S5)	6/23/2008	6/26/2008	-	8	448	0.26
181 (S6)	8/14/2008	8/14/2008	10	10	588	0.25
182 (S7)	1/17/2009	1/17/2009	10	9	1580	0.26
183 (S8)	5/14/2009	5/14/2009	10	10	722	0.24
186 (S9)	7/22/2009	7/22/2009	10	9	909	0.24
189 (S10)	11/20/2009	11/20/2009	10	9	1462	0.30
191 (S11)	3/17/2010	3/20/2010	-	8	1114	0.39
192 (S12)	5/16/2010	5/16/2010	9	9	907	0.25
196 (S13)	7/19/2010	7/20/2010	10	10	1047	0.46
197 (S14)	8/10/2010	8/13/2010	-	10	779	0.24
198 (S15)	11/18/2010	11/22/2010	12	8	1486	0.33
201 (S16)	3/9/2011	3/9/2011	11	11	1510	0.16
203 (S17)	5/20/2011	5/21/2011	11	11	903	0.56
206 (S18)	7/10/2011	7/12/2011	11	11	377	0.31

DSR						
Sampling Trip Description (Water Quality)				TDS (mg/L)		
Trip Number	Start Date	End Date	No. Sites Visited	No. Evalu-ations	Average	CV
26 (S1)	6/3/2003	6/5/2003	-	2	2581	0.26
29 (S2)	6/25/2003	7/2/2003	-	0		
32 (S3)	7/24/2003	7/31/2003	-	4	3165	0.29
38 (S4)	10/25/2003	10/25/2003	6	0		
41 (S5)	1/12/2004	1/17/2004	-	6	3177	0.11
43 (S6)	3/17/2004	3/19/2004	-	0		
45 (S7)	5/1/2004	5/6/2004	-	6	2236	0.11
48 (S8)	6/3/2004	6/4/2004	6	0		
52 (S9)	6/29/2004	6/30/2004	-	6	2414	0.22
56 (S10)	8/4/2004	8/6/2004	-	0		
62 (S11)	11/6/2004	11/7/2004	-	6	3504	0.14
65 (S12)	1/12/2005	1/17/2005	-	0		
67 (S13)	3/16/2005	3/18/2005	-	6	3643	0.11
74 (S14)	6/30/2005	7/1/2005	-	0		
77 (S15)	7/21/2005	7/22/2005	-	6	2001	0.06
80 (S16)	8/11/2005	8/19/2005	-	0		
84 (S17)	12/3/2005	12/3/2005	6	6	3413	0.16
86 (S18)	1/14/2006	1/14/2006	6	0		
89 (S19)	3/13/2006	3/15/2006	-	6	3397	0.14
91 (S20)	5/16/2006	5/16/2006	6	0		
95 (S21)	6/12/2006	6/16/2006	-	6	3140	0.21
99 (S22)	7/11/2006	7/13/2006	-	0		
102 (S23)	8/7/2006	8/10/2006	-	6	2756	0.17
106 (S24)	11/20/2006	11/20/2006	6	0		

Table 3.6 (Cont.)

DSR						
Sampling Trip Description (Water Quality Trip)				TDS (mg/L)		
Trip Number	Start Date	End Date	No. Sites Visited	No. Evalu-ations	Average	CV
109 (S25)	3/11/2007	3/12/2007	6	6	3239	0.04
112 (S26)	5/15/2007	5/18/2007	-	0		
115 (S27)	6/21/2007	6/22/2007	-	6	2678	0.07
120 (S28)	7/23/2007	7/24/2007	-	0		
122 (S29)	8/13/2007	8/15/2007	-	6	2975	0.08
124 (S30)	11/18/2007	11/23/2007	-	6	3131	0.14
126 (S31)	1/16/2008	1/16/2008	6	0		
130 (S32)	5/21/2008	5/21/2008	6	6	3112	0.12
133 (S33)	6/23/2008	6/26/2008	-	0		
136 (S34)	7/16/2008	7/16/2008	6	6	1070	0.09
140 (S35)	11/21/2008	11/21/2008	6	6	3057	0.10
142 (S36)	1/15/2009	1/18/2009	-	0		
143 (S37)	3/12/2009	3/12/2009	6	6	3196	0.11
146 (S38)	6/25/2009	6/25/2009	6	6	3246	0.10
150 (S39)	8/28/2009	8/28/2009	6	6	3052	0.07
152 (S40)	1/5/2010	1/7/2010	-	6	2449	0.21
153 (S41)	3/15/2010	3/19/2010	-	6	3603	0.08
155 (S42)	6/10/2010	6/10/2010	6	5	2956	0.16
158 (S43)	8/10/2010	8/12/2010	-	6	2670	0.05
159 (S44)	11/18/2010	11/24/2010	-	8	3208	0.18
161 (S45)	3/8/2011	3/9/2011	8	8	3056	0.11
163 (S46)	5/19/2011	5/21/2011	8	8	3220	0.16
166 (S47)	8/16/2011	8/19/2011	-	2	2196	0.77
168 (S48)	1/5/2012	1/9/2012	-	6	3230	0.07
173 (S49)	8/14/2012	8/16/2012	-	6	2887	0.13

Table 3.7. Abridged statistical summary of principal cation concentrations in water samples gathered from the Arkansas River within the USR.

Sampling Trip Description (Water Quality)				C_{Ca} (mg/L)			C_{Na} (mg/L)			C_{Mg} (mg/L)		
Trip Number	Start Date	End Date	No. Sites Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
155 (S1)	6/17/2006	6/20/2006	-	10	62.6	0.18	10	41.6	0.21	10	19.6	0.17
168 (S2)	5/21/2007	5/24/2007	-	9	82.1	0.12	9	61.9	0.11	9	25.0	0.12
173 (S3)	10/11/2007	10/11/2007	10	10	106.8	0.13	10	75.6	0.19	10	38.9	0.12
175 (S4)	3/20/2008	3/22/2008	10	10	128.6	0.44	10	138.8	0.50	10	53.5	0.41
178 (S5)	6/23/2008	6/26/2008	-	8	58.0	0.24	8	33.3	0.39	8	18.9	0.28
181 (S6)	8/14/2008	8/14/2008	10	10	75.1	0.20	10	55.9	0.37	10	23.9	0.25
182 (S7)	1/17/2009	1/17/2009	10	9	220.1	0.27	9	139.1	0.25	9	71.0	0.22
183 (S8)	5/14/2009	5/14/2009	10	10	93.1	0.18	10	60.1	0.25	10	30.7	0.24
186 (S9)	7/22/2009	7/22/2009	10	9	120.7	0.30	9	87.3	0.29	9	42.1	0.24
189 (S10)	11/20/2009	11/20/2009	10	9	196.0	0.33	9	133.8	0.28	9	69.6	0.29
191 (S11)	3/17/2010	3/20/2010	-	8	134.3	0.37	8	110.6	0.46	8	52.3	0.39
192 (S12)	5/16/2010	5/16/2010	9	9	112.8	0.23	9	87.1	0.33	9	40.7	0.28
196 (S13)	7/19/2010	7/20/2010	10	10	144.5	0.38	10	90.1	0.63	10	47.9	0.45
197 (S14)	8/10/2010	8/13/2010	-	10	110.4	0.23	10	64.1	0.29	10	31.0	0.27
198 (S15)	11/18/2010	11/22/2010	-	8	199.8	0.39	8	126.3	0.33	8	67.6	0.32
201 (S16)	3/9/2011	3/9/2011	11	11	179.1	0.17	11	147.4	0.23	11	71.5	0.15
203 (S17)	5/20/2011	5/21/2011	11	11	112.4	0.46	11	80.7	0.79	11	40.5	0.59
206 (S18)	7/10/2011	7/12/2011	11	11	55.5	0.27	11	28.6	0.38	11	15.9	0.29

Table 3.8. Abridged statistical summary of principal cation concentrations in water samples gathered from the Arkansas River within the DSR.

Sampling Trip Description (Water Quality)				C_{Ca} (mg/L)			C_{Na} (mg/L)			C_{Mg} (mg/L)		
Trip Number	Start Date	End Date	No. Sites Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
26 (S1)	6/3/2003	6/5/2003	-	2	270.0	0.19	2	351.0	0.33	2	136.5	0.21
29 (S2)	6/25/2003	7/2/2003	-	0			0			0		
32 (S3)	7/24/2003	7/31/2003	-	4	303.3	0.24	4	381.3	0.36	4	176.5	0.24
38 (S4)	10/25/2003	10/25/2003	6	0			0			0		
41 (S5)	1/12/2004	1/17/2004	-	6	372.5	0.04	6	409.2	0.12	6	131.2	0.07
43 (S6)	3/17/2004	3/19/2004	-	0			0			0		
45 (S7)	5/1/2004	5/6/2004	-	6	236.2	0.08	6	286.7	0.16	6	118.8	0.11
48 (S8)	6/3/2004	6/4/2004	6	0			0			0		
52 (S9)	6/29/2004	6/30/2004	-	6	243.8	0.18	6	325.7	0.27	6	125.5	0.22
56 (S10)	8/4/2004	8/6/2004	-	0			0			0		
62 (S11)	11/6/2004	11/7/2004	-	6	353.3	0.07	6	498.3	0.20	6	165.0	0.11
65 (S12)	1/12/2005	1/17/2005	-	0			0			0		
67 (S13)	3/16/2005	3/18/2005	-	6	393.7	0.06	6	530.5	0.17	6	183.8	0.10
74 (S14)	6/30/2005	7/1/2005	-	0			0			0		
77 (S15)	7/21/2005	7/22/2005	-	6	207.5	0.07	6	251.7	0.09	6	82.5	0.07
80 (S16)	8/11/2005	8/19/2005	-	0			0			0		
84 (S17)	12/3/2005	12/3/2005	6	6	351.8	0.10	6	494.8	0.24	6	151.0	0.14
86 (S18)	1/14/2006	1/14/2006	6	0			0			0		
89 (S19)	3/13/2006	3/15/2006	-	6	329.8	0.10	6	502.5	0.20	6	161.5	0.15
91 (S20)	5/16/2006	5/16/2006	6	0			0			0		
95 (S21)	6/12/2006	6/16/2006	-	6	301.7	0.15	6	454.5	0.32	6	164.7	0.21
99 (S22)	7/11/2006	7/13/2006	-	0			0			0		
102 (S23)	8/7/2006	8/10/2006	-	6	260.8	0.10	6	386.3	0.24	6	144.3	0.14
106 (S24)	11/20/2006	11/20/2006	6	0			0			0		
109 (S25)	3/11/2007	3/12/2007	6	6	326.7	0.03	6	451.3	0.05	6	152.7	0.02
112 (S26)	5/15/2007	5/18/2007	-	0			0			0		
115 (S27)	6/21/2007	6/22/2007	-	6	295.0	0.06	6	329.3	0.10	6	124.8	0.05
120 (S28)	7/23/2007	7/24/2007	-	0			0			0		

Table 3.8 (Cont.)

Sampling Trip Description (Water Quality)				C_{Ca} (mg/L)			C_{Na} (mg/L)			C_{Mg} (mg/L)		
Trip Number	Start Date	End Date	No. Sites Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
122 (S29)	8/13/2007	8/15/2007	-	6	296.3	0.05	6	391.0	0.11	6	127.8	0.07
124 (S30)	11/18/2007	11/23/2007	-	6	315.7	0.09	6	386.7	0.16	6	181.0	0.13
126 (S31)	1/16/2008	1/16/2008	6	0			0			0		
130 (S32)	5/21/2008	5/21/2008	6	6	325.0	0.06	6	464.3	0.17	6	177.0	0.13
133 (S33)	6/23/2008	6/26/2008	-	0			0			0		
136 (S34)	7/16/2008	7/16/2008	6	6	128.0	0.07	6	121.5	0.12	6	52.7	0.11
140 (S35)	11/21/2008	11/21/2008	6	6	313.8	0.07	6	420.7	0.14	6	145.0	0.10
142 (S36)	1/15/2009	1/18/2009	-	0			0			0		
143 (S37)	3/12/2009	3/12/2009	6	6	321.5	0.08	6	417.0	0.14	6	140.2	0.09
146 (S38)	6/25/2009	6/25/2009	6	6	307.3	0.04	6	431.2	0.15	6	173.0	0.10
150 (S39)	8/28/2009	8/28/2009	6	6	285.8	0.03	6	395.5	0.11	6	158.8	0.06
152 (S40)	1/5/2010	1/7/2010	-	6	234.2	0.24	6	328.7	0.24	6	129.7	0.25
153 (S41)	3/15/2010	3/19/2010	-	6	366.3	0.04	6	477.0	0.10	6	193.0	0.07
155 (S42)	6/10/2010	6/10/2010	6	5	294.4	0.11	5	366.4	0.24	5	154.8	0.15
158 (S43)	8/10/2010	8/12/2010	-	6	281.2	0.07	6	343.3	0.07	6	145.7	0.07
159 (S44)	11/18/2010	11/24/2010	-	8	321.4	0.19	8	436.3	0.23	8	175.4	0.17
161 (S45)	3/8/2011	3/9/2011	8	8	297.3	0.15	8	410.4	0.15	8	167.1	0.10
163 (S46)	5/19/2011	5/21/2011	8	8	306.6	0.10	8	431.4	0.22	8	172.5	0.14
166 (S47)	8/16/2011	8/19/2011	-	2	216.5	0.65	2	290.0	0.91	2	115.5	0.81
168 (S48)	1/5/2012	1/9/2012	-	6	340.3	0.05	6	425.5	0.11	6	177.0	0.06
173 (S49)	8/14/2012	8/16/2012	-	6	286.7	0.10	6	386.5	0.19	6	155.5	0.14

Table 3.9. Abridged statistical summary of principal anion concentrations in water samples gathered from the Arkansas River within the USR.

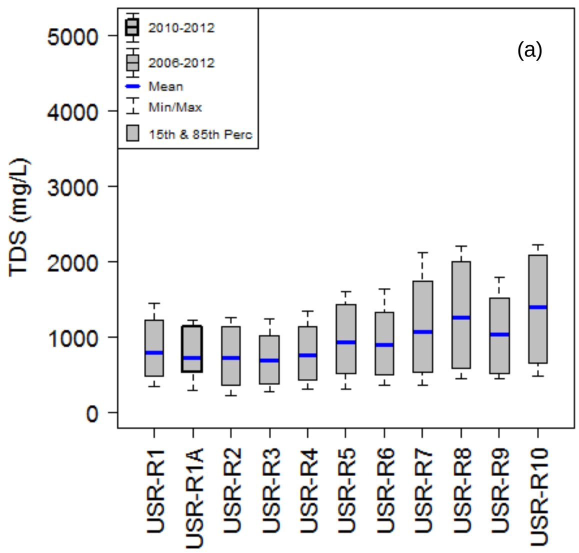
Sampling Trip Description (Water Quality)				C_{SO_4-S} (mg/L)			C_{HCO_3} (mg/L)			C_{Cl} (mg/L)		
Trip Number	Start Date	End Date	No. Sites Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
155 (S1)	6/17/2006	6/20/2006	-	10	54.7	0.27	10	102.6	0.26	10	13.5	0.23
168 (S2)	5/21/2007	5/24/2007	-	9	70.2	0.14	9	113.1	0.57	9	18.3	0.07
173 (S3)	10/11/2007	10/11/2007	10	10	125.9	0.18	10	190.7	0.07	10	27.4	0.16
175 (S4)	3/20/2008	3/22/2008	10	10	203.4	0.45	10	189.7	0.20	10	55.9	0.34
178 (S5)	6/23/2008	6/26/2008	-	8	65.8	0.34	8	118.1	0.12	8	14.6	0.37
181 (S6)	8/14/2008	8/14/2008	10	10	87.5	0.34	10	133.5	0.09	10	22.0	0.35
182 (S7)	1/17/2009	1/17/2009	10	9	263.3	0.34	9	278.7	0.10	9	50.7	0.22
183 (S8)	5/14/2009	5/14/2009	10	10	112.9	0.35	10	163.0	0.07	10	20.9	0.21
186 (S9)	7/22/2009	7/22/2009	10	9	150.1	0.29	9	156.3	0.14	9	31.1	0.30
189 (S10)	11/20/2009	11/20/2009	10	9	244.0	0.37	9	254.7	0.13	9	47.0	0.15
191 (S11)	3/17/2010	3/20/2010	-	8	186.9	0.48	8	186.8	0.14	8	41.6	0.33
192 (S12)	5/16/2010	5/16/2010	9	9	151.4	0.32	9	160.7	0.12	9	34.0	0.33
196 (S13)	7/19/2010	7/20/2010	10	10	177.8	0.53	10	179.5	0.26	10	28.5	0.58
197 (S14)	8/10/2010	8/13/2010	-	10	126.1	0.30	10	151.7	0.13	10	22.8	0.22
198 (S15)	11/18/2010	11/22/2010	-	8	254.6	0.40	8	255.9	0.14	8	44.8	0.22
201 (S16)	3/9/2011	3/9/2011	11	11	263.6	0.20	11	248.3	0.08	11	45.9	0.16
203 (S17)	5/20/2011	5/21/2011	11	11	145.0	0.72	11	195.7	0.18	11	29.5	0.63
206 (S18)	7/10/2011	7/12/2011	11	11	50.2	0.44	11	109.5	0.16	11	8.8	0.37

Table 3.10. Abridged statistical summary of principal anion concentrations in water samples gathered from the Arkansas River within the DSR.

Sampling Trip Description (Water Quality)				C_{SO_4-S} (mg/L)			C_{HCO_3} (mg/L)			C_{Cl} (mg/L)		
Trip Number	Start Date	End Date	No. Sites Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
26 (S1)	6/3/2003	6/5/2003	-	2	502.0	0.25	2	221.0	0.39	2	88.0	0.23
29 (S2)	6/25/2003	7/2/2003	-	0			0			0		
32 (S3)	7/24/2003	7/31/2003	-	4	632.0	0.30	4	281.0	0.31	4	98.0	0.23
38 (S4)	10/25/2003	10/25/2003	6	0			0			0		
41 (S5)	1/12/2004	1/17/2004	-	6	569.0	0.08	6	413.7	0.39	6	121.5	0.11
43 (S6)	3/17/2004	3/19/2004	-	0			0			0		
45 (S7)	5/1/2004	5/6/2004	-	6	434.2	0.11	6	193.5	0.17	6	78.7	0.10
48 (S8)	6/3/2004	6/4/2004	6	0			0			0		
52 (S9)	6/29/2004	6/30/2004	-	6	452.8	0.23	6	242.5	0.18	6	84.8	0.22
56 (S10)	8/4/2004	8/6/2004	-	0			0			0		
62 (S11)	11/6/2004	11/7/2004	-	6	658.2	0.15	6	335.7	0.08	6	137.0	0.17
65 (S12)	1/12/2005	1/17/2005	-	0			0			0		
67 (S13)	3/16/2005	3/18/2005	-	6	682.3	0.11	6	348.0	0.04	6	122.3	0.14
74 (S14)	6/30/2005	7/1/2005	-	0			0			0		
77 (S15)	7/21/2005	7/22/2005	-	6	370.5	0.06	6	251.0	0.08	6	76.8	0.08
80 (S16)	8/11/2005	8/19/2005	-	0			0			0		
84 (S17)	12/3/2005	12/3/2005	6	6	644.7	0.17	6	333.8	0.05	6	128.5	0.19
86 (S18)	1/14/2006	1/14/2006	6	0			0			0		
89 (S19)	3/13/2006	3/15/2006	-	6	637.0	0.14	6	358.0	0.06	6	114.0	0.17
91 (S20)	5/16/2006	5/16/2006	6	0			0			0		
95 (S21)	6/12/2006	6/16/2006	-	6	596.0	0.20	6	274.5	0.30	6	101.3	0.20
99 (S22)	7/11/2006	7/13/2006	-	0			0			0		
102 (S23)	8/7/2006	8/10/2006	-	6	514.2	0.15	6	263.2	0.09	6	100.2	0.17
106 (S24)	11/20/2006	11/20/2006	6	0			0			0		
109 (S25)	3/11/2007	3/12/2007	6	6	609.8	0.06	6	322.3	0.05	6	122.3	0.04
112 (S26)	5/15/2007	5/18/2007	-	0			0			0		

Table 3.10 (Cont.)

Sampling Trip Description (Water Quality)				C_{SO_4-S} (mg/L)			C_{HCO_3} (mg/L)			C_{Cl} (mg/L)		
Trip Number	Start Date	End Date	No. Sites Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
115 (S27)	6/21/2007	6/22/2007	-	6	500.5	0.08	6	294.8	0.04	6	106.0	0.09
120 (S28)	7/23/2007	7/24/2007	-	0			0			0		
122 (S29)	8/13/2007	8/15/2007	-	6	573.8	0.08	6	285.7	0.05	6	122.3	0.08
124 (S30)	11/18/2007	11/23/2007	-	6	593.2	0.16	6	306.7	0.06	6	131.0	0.14
126 (S31)	1/16/2008	1/16/2008	6	0			0			0		
130 (S32)	5/21/2008	5/21/2008	6	6	561.5	0.14	6	295.8	0.04	6	131.0	0.13
133 (S33)	6/23/2008	6/26/2008	-	0			0			0		
136 (S34)	7/16/2008	7/16/2008	6	6	186.0	0.10	6	157.5	0.02	6	39.3	0.11
140 (S35)	11/21/2008	11/21/2008	6	6	565.7	0.11	6	328.7	0.05	6	121.3	0.11
142 (S36)	1/15/2009	1/18/2009	-	0			0			0		
143 (S37)	3/12/2009	3/12/2009	6	6	613.8	0.11	6	311.2	0.05	6	141.3	0.23
146 (S38)	6/25/2009	6/25/2009	6	6	629.5	0.12	6	300.5	0.03	6	115.0	0.14
150 (S39)	8/28/2009	8/28/2009	6	6	589.2	0.08	6	301.7	0.04	6	112.3	0.11
152 (S40)	1/5/2010	1/7/2010	-	6	452.5	0.22	6	280.2	0.13	6	94.3	0.20
153 (S41)	3/15/2010	3/19/2010	-	6	703.7	0.09	6	302.0	0.02	6	126.5	0.06
155 (S42)	6/10/2010	6/10/2010	6	5	575.2	0.17	5	277.8	0.12	5	102.8	0.21
158 (S43)	8/10/2010	8/12/2010	-	6	505.3	0.06	6	257.7	0.08	6	94.2	0.04
159 (S44)	11/18/2010	11/24/2010	-	8	592.8	0.20	8	340.5	0.07	8	123.4	0.21
161 (S45)	3/8/2011	3/9/2011	8	8	563.3	0.17	8	358.6	0.23	8	104.4	0.16
163 (S46)	5/19/2011	5/21/2011	8	8	613.0	0.15	8	329.1	0.15	8	128.0	0.26
166 (S47)	8/16/2011	8/19/2011	-	2	414.5	0.80	2	220.5	0.45	2	85.5	0.92
168 (S48)	1/5/2012	1/9/2012	-	6	617.7	0.07	6	295.8	0.11	6	110.5	0.06
173 (S49)	8/14/2012	8/16/2012	-	6	546.0	0.12	6	281.3	0.09	6	106.5	0.17



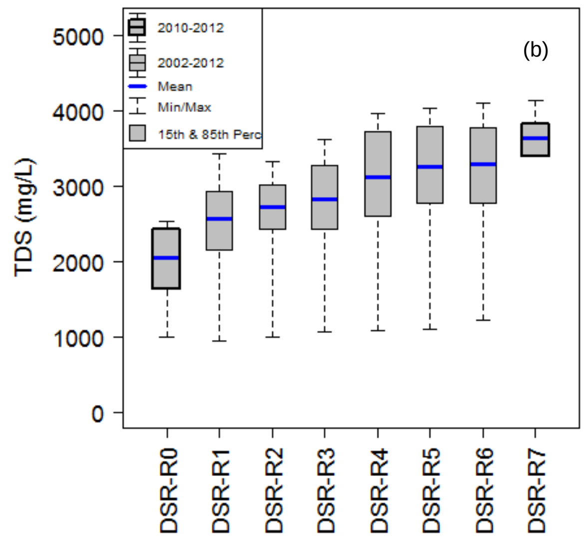


Figure 3.14. Box-and-whisker plots of TDS measured at locations along the Arkansas River in (a) the USR and (b) the DSR.

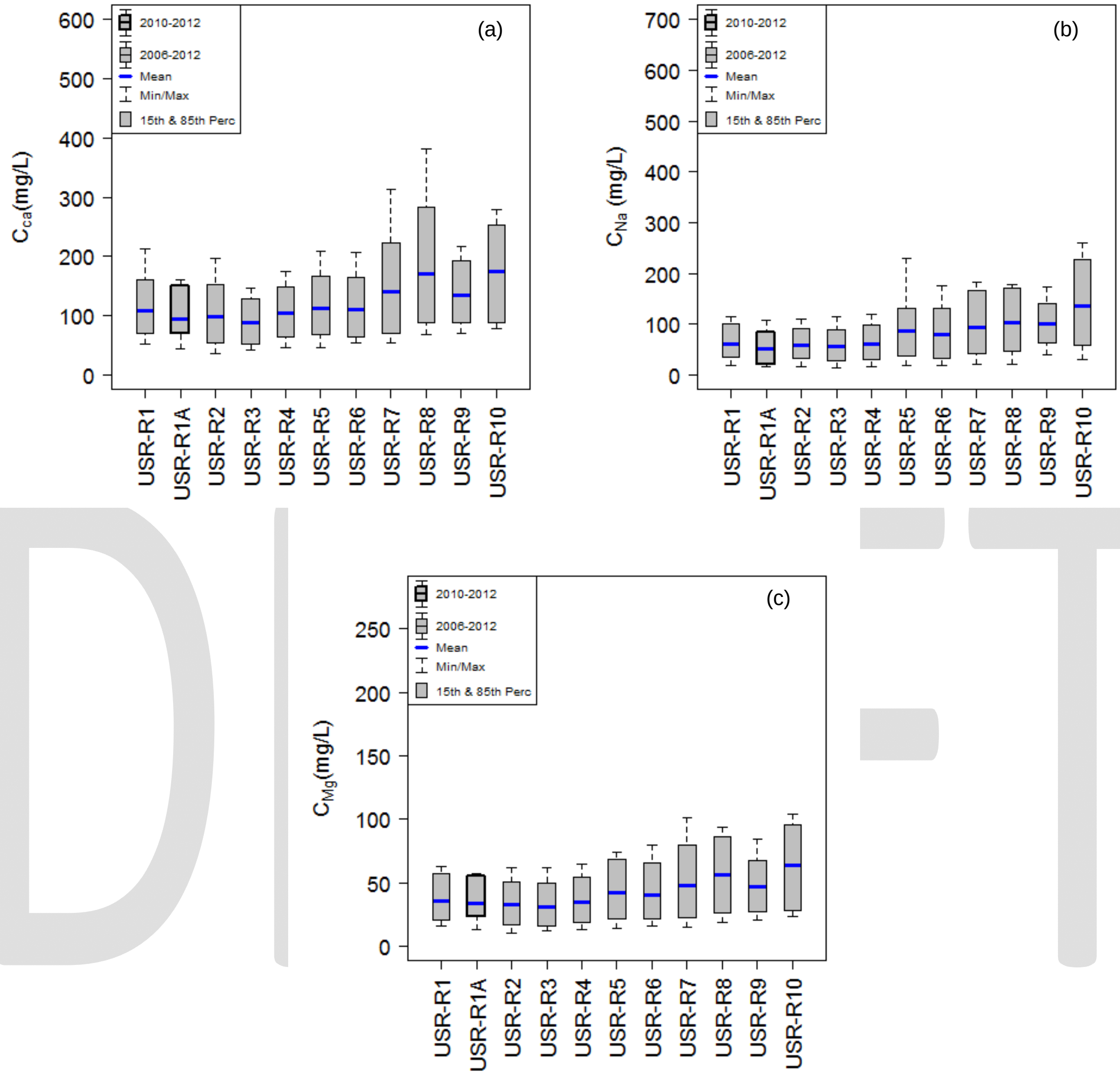


Figure 3.15. Box-and-whisker plots of (a) C_{Ca}, (b) C_{Na}, and (c) C_{Mg} measured at locations along the Arkansas River in the USR.

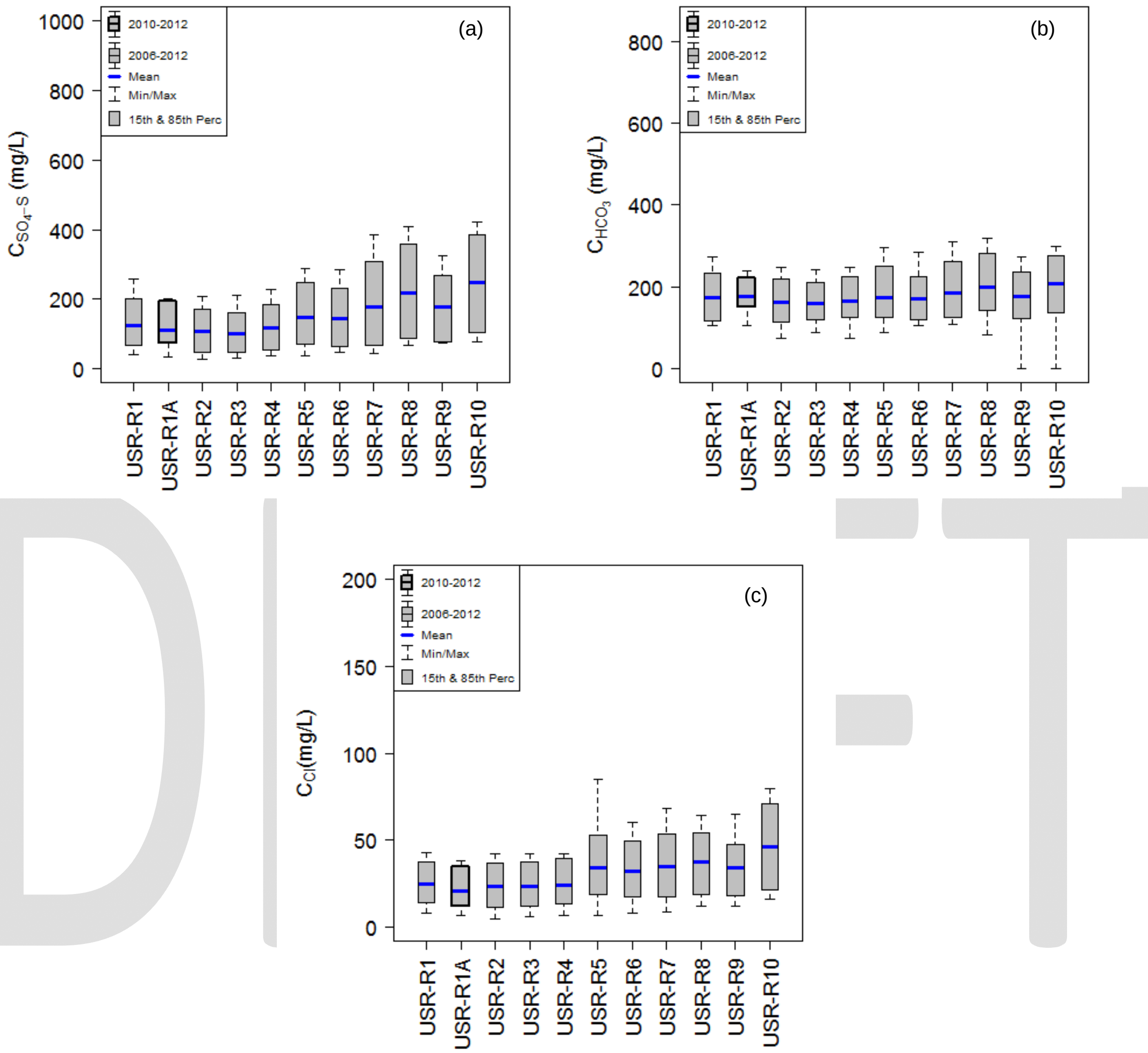


Figure 3.16. Box-and-whisker plots of (a) C_{SO_4-S} , (b) C_{HCO_3} , and (c) C_{Cl} measured at locations along the Arkansas River in the USR.

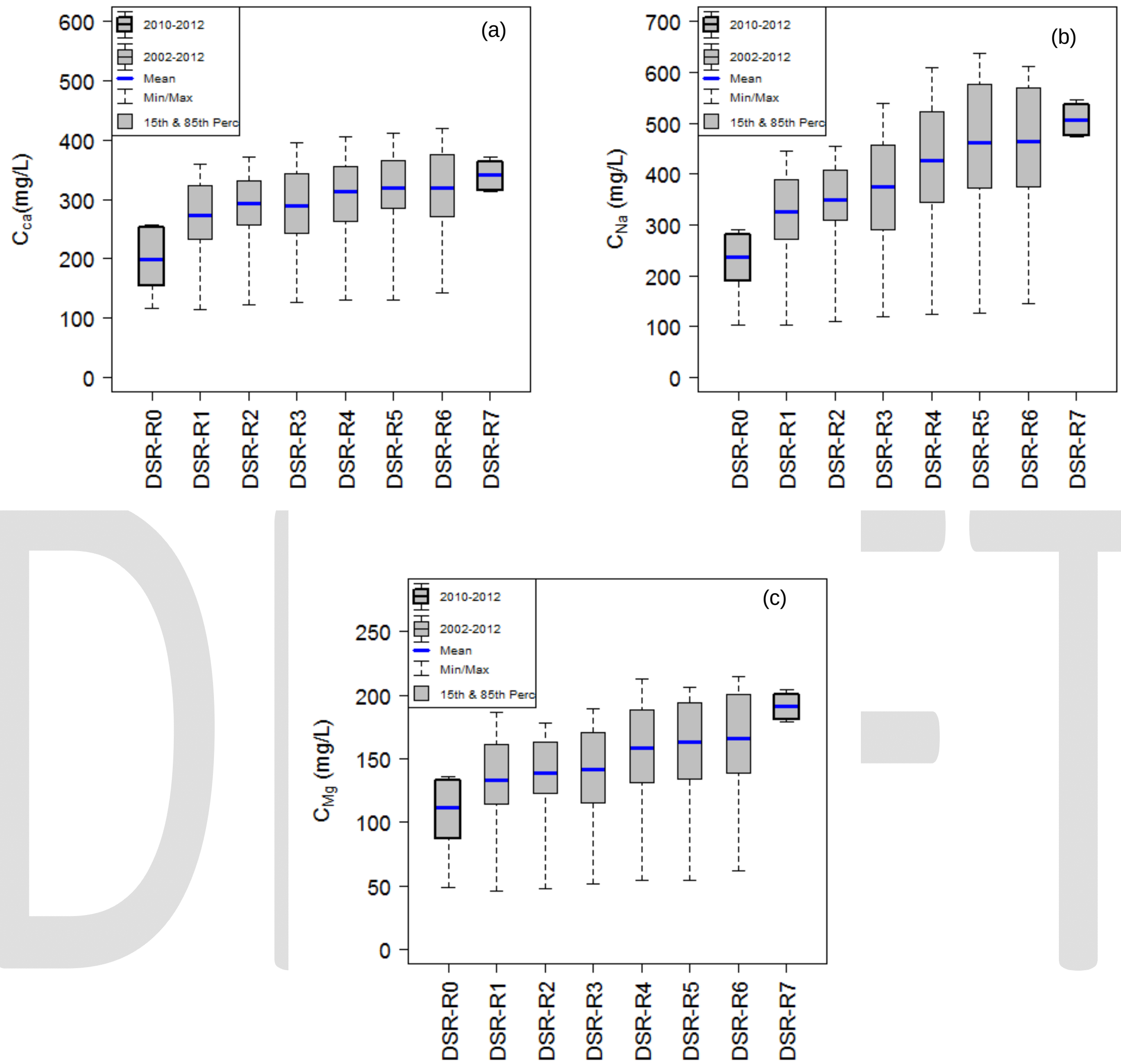


Figure 3.17. Box-and-whisker plots of (a) C_{Ca}, (b) C_{Na}, and (c) C_{Mg} measured at locations along the Arkansas River in the DSR.

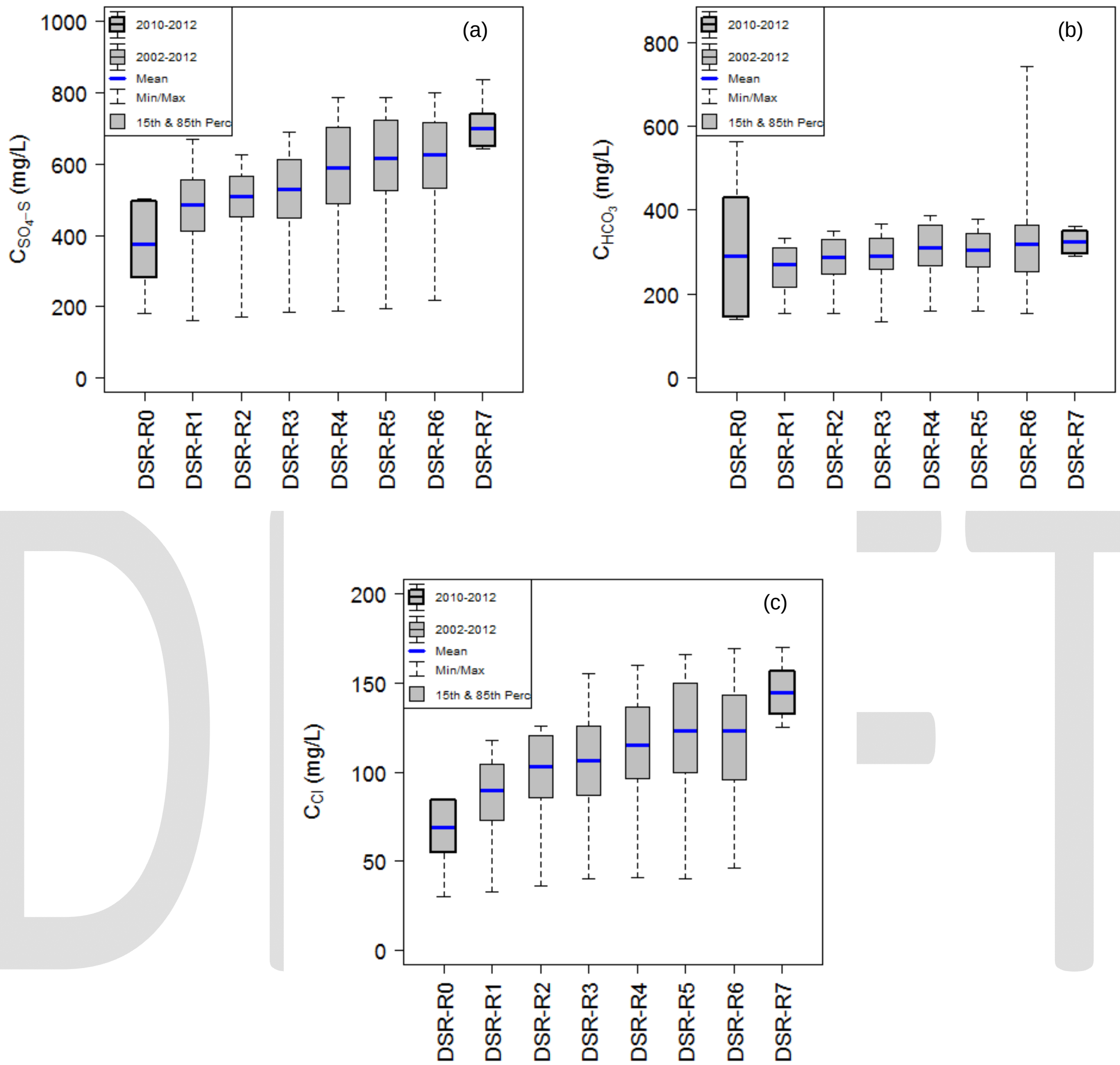


Figure 3.18. Box-and-whisker plots of (a) C_{SO_4-S} , (b) C_{HCO_3} , and (c) C_{Cl} measured at locations along the Arkansas River in the DSR.

3.3.2.2.2 Nitrate in the Surface Water in the LARB Study Regions

Over the last few years growing attention has been given to nutrient pollution in the waterways of Colorado with interim standards now in place for N and P. Figure 3.19 displays histograms of NO_3-N concentration, C_{NO_3-N} , in water samples gathered from the Arkansas River over the study periods in the USR and the DSR. For comparison, the interim standard of 2 mg/L for total dissolved N (NO_3 + NO_2 + NH_4) is depicted in the plots. The temporal distribution of C_{NO_3-N} in samples taken along the Arkansas River in the USR and DSR is shown in Figure 3.20. The 85th percentile value of C_{NO_3-N} in the river samples exceeds the total N standard at most locations in the USR and at the two most downstream locations within the DSR. For the samples from tributaries and drains, the 85th percentile value of C_{NO_3-N} is 3.7 mg/L in the USR and 2.2 mg/L in the DSR.

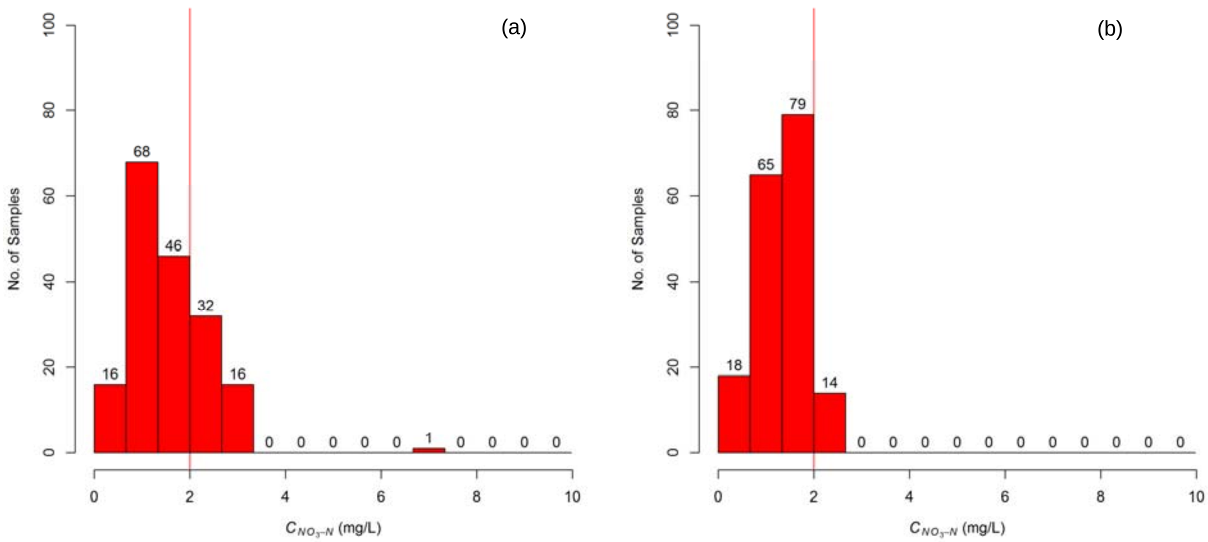


Figure 3.19. Histograms of all C_{NO_3-N} values in water samples taken from the Arkansas River within the (a) USR and (b) DSR during the study periods. The red vertical line depicts the Colorado interim standard of 2 mg/L (85th percentile value).

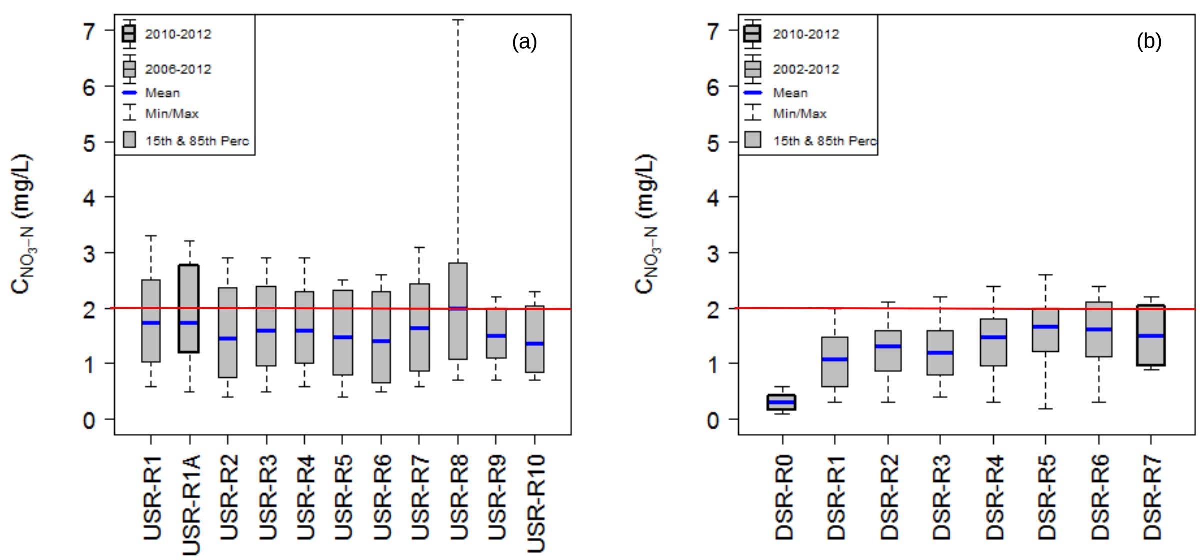


Figure 3.20. Box-and-whisker plots of C_{NO_3-N} measured at locations along the Arkansas River in (a) the USR and (b) the DSR. The red horizontal line depicts the interim standard of 2 mg/L (85th percentile value) for total dissolved N.

3.3.2.2.3 Dissolved Selenium and Uranium in the Surface Water in the LARB Study Regions

Summary statistics for dissolved Se concentration, C_{Se}, and dissolved U concentration, C_U, from samples collected from the Arkansas River are included in Tables 3.11 and 3.12 for all sampling events from 2006 – 2011 in the USR and from 2003 – 2011 in the DSR, respectively. Tables A3.6 in Excel File 3A and A3.9 in Excel File 3B on the ARBhwq CD provide similar summaries over all sampled locations in tributaries and drains for each sampling event. During a few events, samples were taken for analysis of both total dissolved Se and SeO_3. Values of SeO_3 concentration, C_{SeO_3}, were found to be about 12% and 13% of C_{Se} in surface water samples from the USR and DSR, respectively. In groundwater samples, C_{SeO_3} made up about 1 to 3% of C_{Se} in both the USR and DSR. The lower fraction of SeO_3 in groundwater may be due to its tendency to sorb to sediments. The major form of dissolved Se was presumed to be selenate, SeO_4, though some dissolved organic Se also may be present.

Histograms of C_{Se} and C_U from surface water samples collected from the Arkansas River in the USR and DSR are provided in Figures 3.21 and 3.22, respectively. Similar histograms for samples collected from the tributaries and drains are shown in Figures 3.23 and 3.24, respectively. The surface water chronic standards of 4.6 μg/L for C_{Se} and 30 μg/L for C_U, defined as the 85th percentile values of a set of samples, are shown as a red vertical line on the appropriate histograms. Values of C_{Se} in water samples from the Arkansas River range from 2.4 to 22.5 μg/L, averaging 8.9 μg/L along the reach, in the USR and from 1.4 to 23 μg/L, averaging 11.1 μg/L, in the DSR. The 85th quantile values are 13.5 μg/L and 15.2 μg/L in the Arkansas River in the USR and DSR, respectively. For C_U, values in the Arkansas River range from 2.4 to 50 μg/L, averaging 15.1 μg/L, in the USR and range from 13.6 to 118 μg/L, averaging 56.5 μg/L, in the DSR.

Table 3.11. Statistical summary of C_{Se} and C_U in water samples gathered from the Arkansas River within the USR.

Sampling Trip Description (Water Quality)				C_{Se} (µg/L)							C_U (µg/L)						
Trip Number	Start Date	End Date	No. Sites Visited	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile
155 (S1)	6/17/2006	6/20/2006	-	10	4.4	3.3	5.3	0.15	3.8	5.2	0						
168 (S2)	5/21/2007	5/24/2007	-	9	6.2	5.5	7.1	0.09	5.7	6.8	2	8.6	7.0	10.1	0.26	7.5	9.6
173 (S3)	10/11/2007	10/11/2007	10	10	9.1	8.0	10.1	0.08	8.4	9.9	0						
175 (S4)	3/20/2008	3/22/2008	10	10	12.1	10.2	14.9	0.14	10.3	13.8	10	15.7	8.1	34.5	0.50	9.8	20.6
178 (S5)	6/23/2008	6/26/2008	-	8	4.1	3.6	5.2	0.14	3.7	4.8	8	6.9	4.7	9.9	0.29	5.0	9.7
181 (S6)	8/14/2008	8/14/2008	10	10	5.3	4.3	6.4	0.13	4.6	5.9	10	8.8	5.2	12.2	0.29	5.7	11.1
182 (S7)	1/17/2009	1/17/2009	10	9	14.4	12.4	16.9	0.10	13.3	15.9	9	25.6	15.1	37.2	0.34	15.9	34.8
183 (S8)	5/14/2009	5/14/2009	10	10	8.0	7.2	9.2	0.08	7.5	8.7	10	15.0	7.3	49.8	0.87	7.4	19.9
186 (S9)	7/22/2009	7/22/2009	10	9	7.4	5.1	15.0	0.41	5.4	7.7	9	12.0	6.6	15.1	0.24	10.6	15.0
189 (S10)	11/20/2009	11/20/2009	10	9	12.6	11.0	15.6	0.12	11.2	13.9	9	22.1	12.3	37.4	0.44	12.9	32.5
191 (S11)	3/17/2010	3/20/2010	-	8	11.3	10.4	12.5	0.07	10.6	12.4	8	17.5	11.0	35.0	0.47	13.0	24.5
192 (S12)	5/16/2010	5/16/2010	9	8	10.4	6.9	22.5	0.48	7.8	9.8	9	17.0	9.5	41.8	0.61	9.8	22.5
196 (S13)	7/19/2010	7/20/2010	10	9	8.8	5.7	12.0	0.22	7.0	10.6	10	16.0	7.1	30.9	0.50	8.2	23.4
197 (S14)	8/10/2010	8/13/2010	-	10	6.9	5.4	7.9	0.13	5.9	7.8	10	9.9	5.7	15.8	0.31	7.1	12.9
198 (S15)	11/18/2010	11/22/2010	12	11	13.2	11.7	15.3	0.08	12.2	14.1	10	22.7	12.3	33.5	0.41	13.0	32.2
201 (S16)	3/9/2011	3/9/2011	11	11	14.0	13.1	14.7	0.04	13.4	14.6	11	21.5	15.7	29.4	0.24	16.6	26.7
203 (S17)	5/20/2011	5/21/2011	11	11	9.5	7.6	13.4	0.17	8.1	10.8	11	13.9	7.4	36.8	0.65	7.6	20.8
206 (S18)	7/10/2011	7/12/2011	11	11	3.4	2.4	5.0	0.22	2.7	4.0	11	4.4	2.4	7.9	0.37	3.0	5.8

Table 3.12. Statistical summary of C_{Se} and C_U in water samples gathered from the Arkansas River within the DSR.

Sampling Trip Description (Water Quality)				C_{Se} (µg/L)							C_U (µg/L)						
Trip Number	Start Date	End Date	No. Sites Visited	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile
26 (S1)	6/3/2003	6/5/2003	-	2	8.4	7.6	9.2	0.13	7.8	8.9	0						
29 (S2)	6/25/2003	7/2/2003	-	4	11.0	6.2	17.8	0.44	7.7	14.5	0						
32 (S3)	7/24/2003	7/31/2003	-	4	11.4	6.2	19.2	0.51	6.9	16.1	0						
38 (S4)	10/25/2003	10/25/2003	6	6	13.4	7.7	23.0	0.45	8.5	19.1	0						
41 (S5)	1/12/2004	1/17/2004	-	6	11.3	5.4	17.0	0.42	5.8	15.2	0						
43 (S6)	3/17/2004	3/19/2004	-	6	14.8	10.4	20.8	0.24	12.1	17.1	0						
45 (S7)	5/1/2004	5/6/2004	-	6	8.9	7.7	11.6	0.16	7.8	10.0	0						
48 (S8)	6/3/2004	6/4/2004	6	6	12.8	8.8	17.3	0.24	10.3	15.1	0						
52 (S9)	6/29/2004	6/30/2004	-	6	9.0	7.7	10.8	0.12	8.1	9.7	0						
56 (S10)	8/4/2004	8/6/2004	-	6	8.7	6.6	13.4	0.29	6.7	10.7	0						
62 (S11)	11/6/2004	11/7/2004	-	6	11.7	8.8	15.9	0.20	9.9	13.1	0						
65 (S12)	1/12/2005	1/17/2005	-	6	13.0	10.6	16.4	0.15	11.8	14.2	0						
67 (S13)	3/16/2005	3/18/2005	-	6	14.0	11.9	16.8	0.11	13.1	15.0	0						
74 (S14)	6/30/2005	7/1/2005	-	6	5.0	4.2	5.9	0.12	4.4	5.4	0						
77 (S15)	7/21/2005	7/22/2005	-	6	5.7	5.1	6.7	0.09	5.4	6.0	0						
80 (S16)	8/11/2005	8/19/2005	-	6	10.3	7.8	15.4	0.28	7.8	12.1	0						
84 (S17)	12/3/2005	12/3/2005	6	6	12.3	9.3	16.1	0.22	9.8	14.7	0						
86 (S18)	1/14/2006	1/14/2006	6	6	12.5	10.6	15.4	0.13	11.4	13.5	0						
89 (S19)	3/13/2006	3/15/2006	-	6	13.4	10.8	17.9	0.19	11.3	14.8	0						
91 (S20)	5/16/2006	5/16/2006	6	6	11.6	7.0	18.0	0.37	7.6	14.9	2	67.6	41.9	93.2	0.54	49.6	85.5
95 (S21)	6/12/2006	6/16/2006	-	6	10.0	6.3	12.7	0.23	8.2	12.0	0						
99 (S22)	7/11/2006	7/13/2006	-	6	4.7	4.3	5.5	0.09	4.5	5.0	0						
102 (S23)	8/7/2006	8/10/2006	-	6	10.2	7.7	13.2	0.23	7.7	12.6	0						
106 (S24)	11/20/2006	11/20/2006	6	5	8.8	6.4	10.3	0.18	7.6	10.1	0						
109 (S25)	3/11/2007	3/12/2007	6	6	16.0	14.1	18.2	0.09	14.9	17.4	0						
112 (S26)	5/15/2007	5/18/2007	-	6	10.3	8.2	13.2	0.16	9.0	11.5	0						
115 (S27)	6/21/2007	6/22/2007	-	6	10.5	8.9	11.9	0.09	9.9	11.2	0						

Table 3.12 (Cont.)

Sampling Trip Description (Water Quality)				C_{Se} (µg/L)							C_U (µg/L)						
Trip Number	Start Date	End Date	No. Sites Visited	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile
120 (S28)	7/23/2007	7/24/2007	-	5	5.3	4.6	6.3	0.13	4.7	5.8	0						
122 (S29)	8/13/2007	8/15/2007	-	6	10.9	9.3	13.4	0.14	9.6	12.4	0						
124 (S30)	11/18/2007	11/23/2007	-	6	13.8	11.2	16.2	0.14	11.7	15.5	0						
126 (S31)	1/16/2008	1/16/2008	6	6	14.9	13.3	17.3	0.10	13.5	16.2	6	66.7	59.5	70.5	0.06	63.7	69.8
130 (S32)	5/21/2008	5/21/2008	6	6	13.4	10.9	16.6	0.15	11.4	14.8	6	78.5	62.2	106.0	0.20	63.9	87.9
133 (S33)	6/23/2008	6/26/2008	-	0							0						
136 (S34)	7/16/2008	7/16/2008	6	6	5.0	4.5	6.0	0.12	4.5	5.5	6	17.2	13.6	22.8	0.19	14.3	19.4
140 (S35)	11/21/2008	11/21/2008	6	6	12.6	11.2	15.2	0.12	11.3	13.9	6	58.7	53.0	72.0	0.13	53.0	63.8
142 (S36)	1/15/2009	1/18/2009	-	0							0						
143 (S37)	3/12/2009	3/12/2009	6	6	14.8	13.8	16.0	0.06	13.8	15.6	6	62.5	58.0	67.0	0.06	58.8	65.5
146 (S38)	6/25/2009	6/25/2009	6	6	11.3	9.3	13.8	0.14	10.0	12.5	6	50.7	43.5	55.6	0.10	45.5	55.1
150 (S39)	8/28/2009	8/28/2009	6	6	10.8	9.0	14.2	0.16	9.8	11.5	6	51.5	42.6	60.0	0.12	46.0	55.9
152 (S40)	1/5/2010	1/7/2010	-	1	5.1	5.1	5.1		5.1	5.1	6	66.7	56.8	79.0	0.13	58.1	74.5
153 (S41)	3/15/2010	3/19/2010	-	6	13.8	12.2	16.2	0.11	12.6	15.2	6	68.7	59.0	80.0	0.12	61.3	77.8
155 (S42)	6/10/2010	6/10/2010	6	5	11.1	8.9	14.4	0.20	9.1	12.7	5	51.8	40.6	70.3	0.24	41.3	63.6
158 (S43)	8/10/2010	8/12/2010	-	6	9.4	7.9	10.7	0.10	8.9	10.0	6	41.1	36.1	47.5	0.09	38.1	43.8
159 (S44)	11/18/2010	11/24/2010	-	8	13.3	2.7	17.3	0.35	12.2	16.5	8	58.5	19.3	76.8	0.31	52.1	71.8
161 (S45)	3/8/2011	3/9/2011	8	8	13.0	1.4	17.5	0.37	13.1	15.1	8	65.8	18.6	118.0	0.42	53.5	73.4
163 (S46)	5/19/2011	5/21/2011	8	8	14.4	6.5	18.4	0.24	13.3	16.2	8	59.9	28.4	73.9	0.24	55.0	70.9
166 (S47)	8/16/2011	8/19/2011	-	2	9.7	6.1	13.3	0.53	7.2	12.2	2	40.0	15.3	64.6	0.87	22.7	57.2
168 (S48)	1/5/2012	1/9/2012	-	6	17.2	14.8	23.2	0.21	14.8	21.0	6	73.3	65.0	97.7	0.16	67.6	77.1
173 (S49)	8/14/2012	8/16/2012	-	6	11.9	10.8	13.7	0.09	10.9	12.7	6	53.5	46.8	62.5	0.13	47.0	61.1

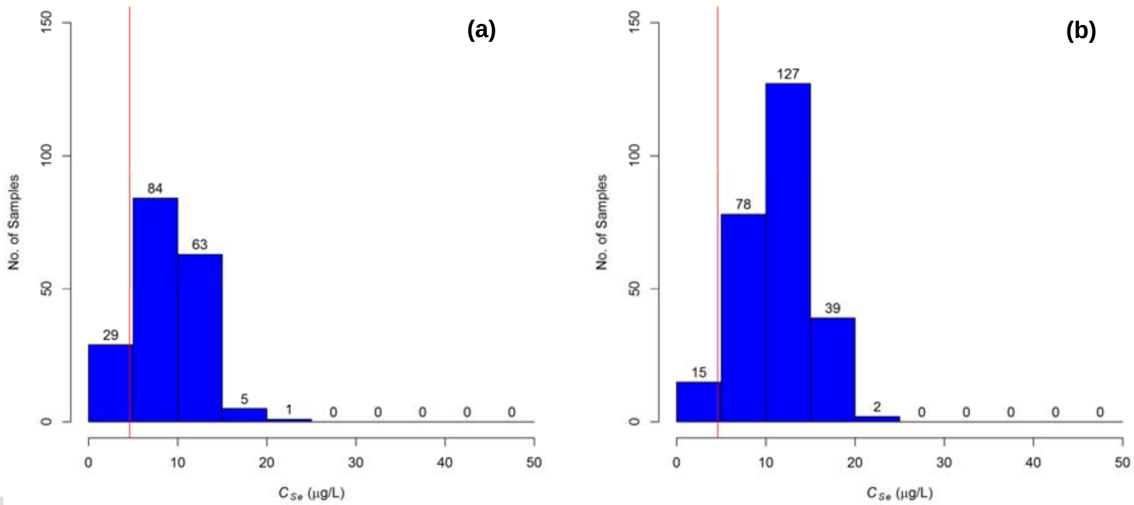


Figure 3.21. Histograms of all C_{Se} values in water samples taken from the Arkansas River within the (a) USR and (b) DSR during the study periods. The red vertical line depicts the chronic standard of 4.6 µg/L (85th percentile value).

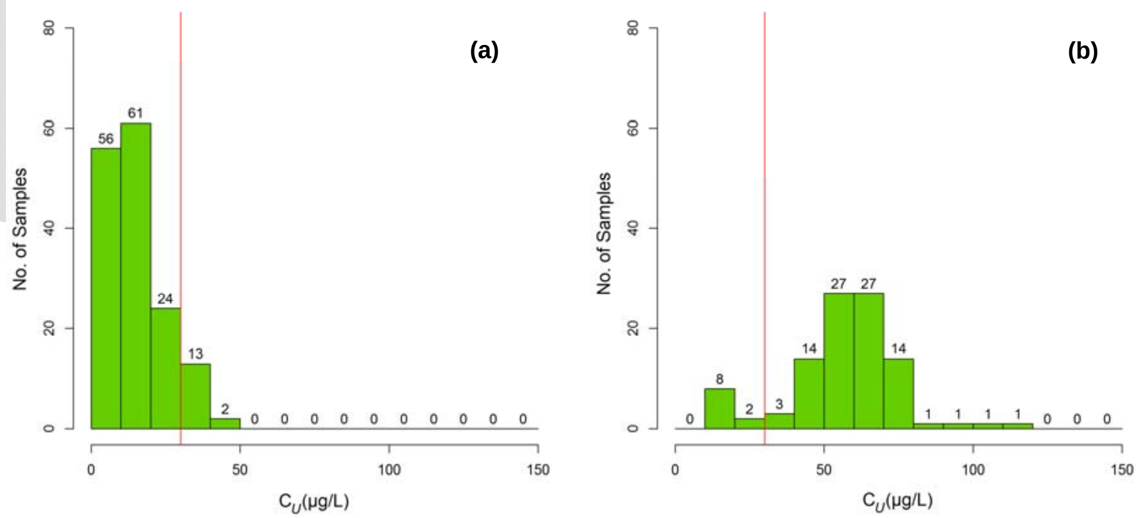


Figure 3.22. Histograms of all C_U values in water samples taken from the Arkansas River within the (a) USR and (b) DSR during the study periods. The red vertical line depicts the chronic standard of 30 µg/L (85th percentile value).

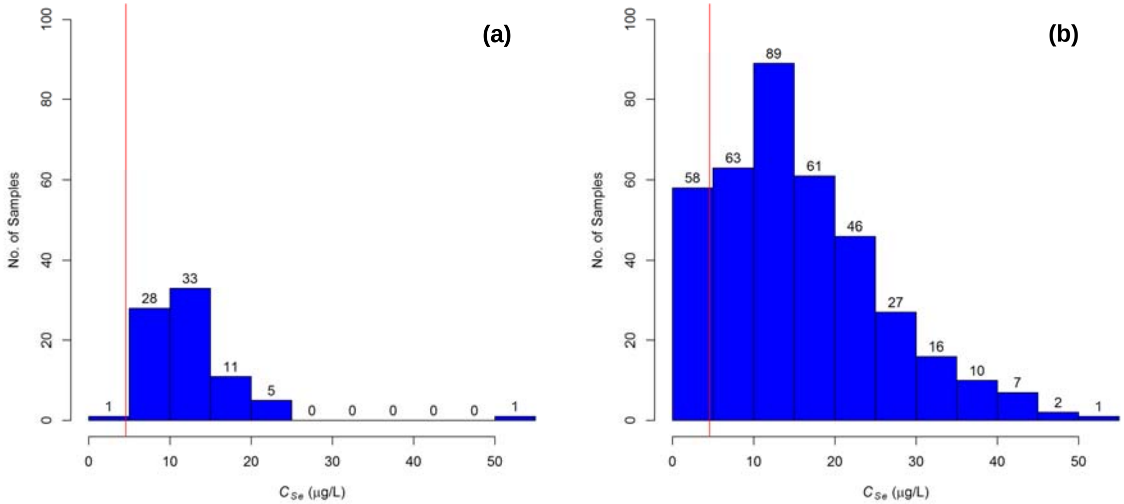


Figure 3.23. Histograms of all C_{Se} values in water samples taken from the tributaries and drains within the (a) USR and (b) DSR during the study periods. The red vertical line depicts the chronic standard of 4.6 µg/L (85th percentile value).

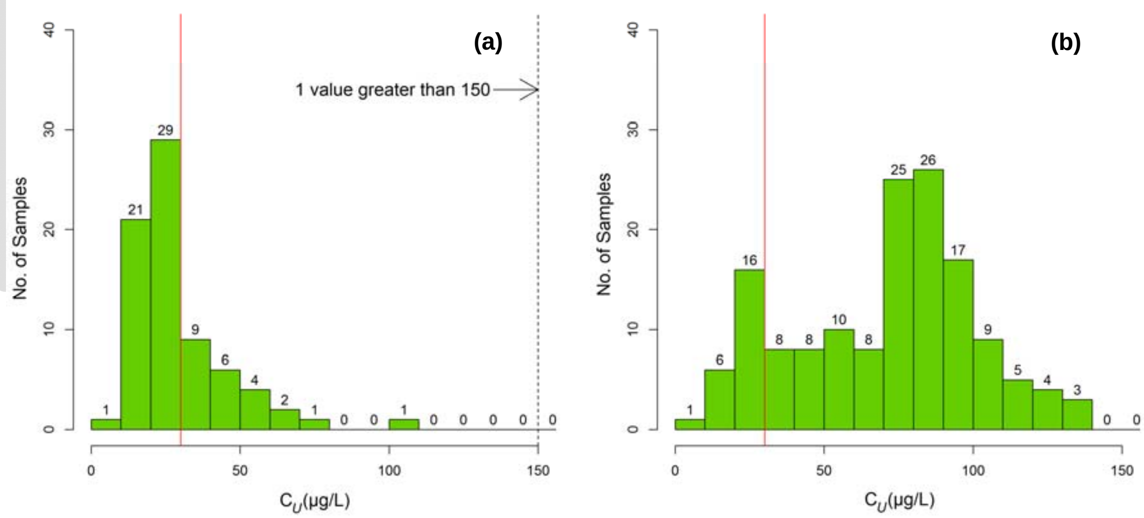


Figure 3.24. Histograms of all C_U values in water samples taken from the Arkansas River within the (a) USR and (b) DSR during the study periods. The red vertical line depicts the chronic standard of 30 µg/L (85th percentile value).

Statistics also are summarized for results collected over the entire data collection period at each routinely-sampled location along the Arkansas River. Box-and-whisker plots for C_{Se} in the USR and DSR organized by sample location along the Arkansas River are shown in Figure 3.25. Similar box-and-whisker graphs are presented in Figure 3.26 for C_U. It is noteworthy that both C_{Se} and C_U appear to drop substantially just downstream of John Martin Reservoir (location DSR-R0). A similar pattern was observed for C_{Se} by Mueller et al. (1991) in data gathered over a four-month period in 1988. These results suggest a dampening role that the reservoir may play through adsorption, chemical reduction, uptake by aquatic plants, and volatilization.

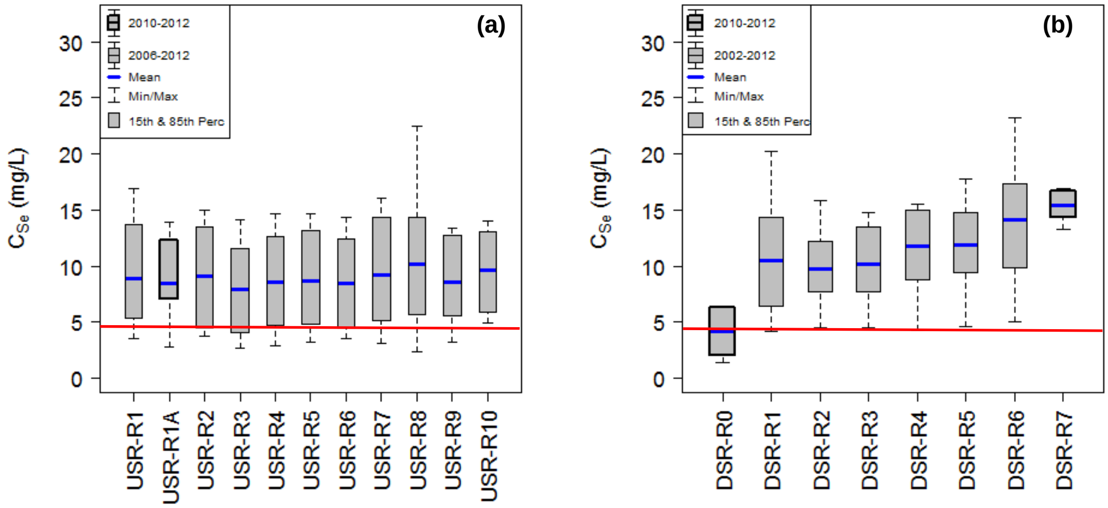


Figure 3.25. Box-and-whisker plots of C_{Se} in water samples from locations along the Arkansas River in (a) the USR and (b) the DSR. The red horizontal line depicts the chronic standard of 4.6 µg/L (85th percentile value).

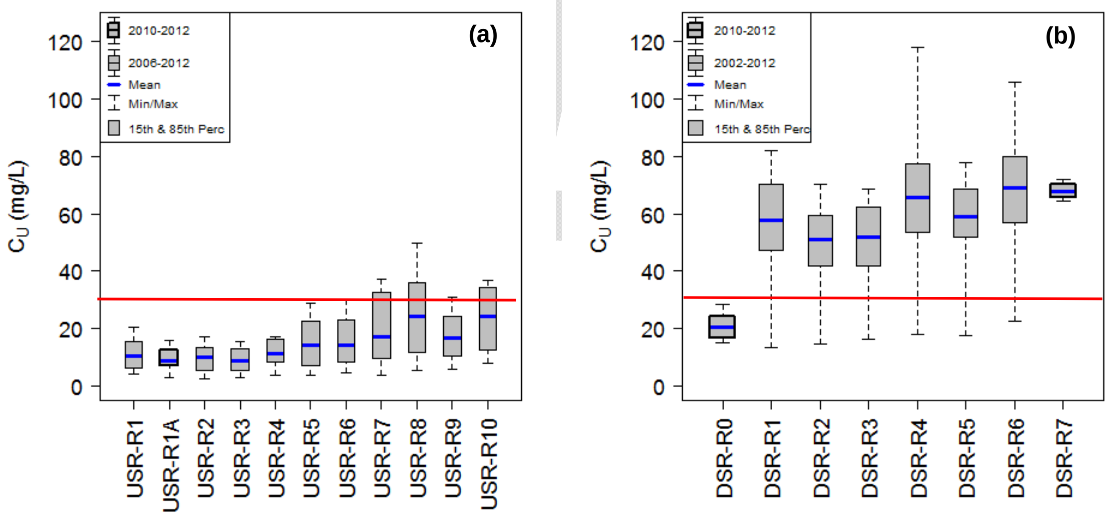


Figure 3.26. Box-and-whisker plots of C_U in water samples from locations along the Arkansas River in (a) the USR and (b) the DSR. The red horizontal line depicts the chronic standard of 30 µg/L (85th percentile value).

The severity of the Se and U problems in the LARB is highlighted by the results presented here. The 85th percentile values of all samples analyzed for C_{Se} along the river are about 3 and 3.3 times greater than the chronic standard in the USR and DSR, respectively. The 85th percentile value of all river samples for C_U is just below the chronic standard in the USR and is 2.4 times greater than the chronic standard in the DSR. A discussion of the factors contributing to these problems, including redox reactions associated with the dissolution of marine shale and its residuum and the inhibition of chemical reduction, is presented in Gates et al. (2009), Bailey et al. (2012), and Bailey et al. (2014).

3.3.2.3 Correlation and Relationships between Surface Water Quality Variables in the LARB Study Regions

The Pearson correlation coefficient was computed as a measure of linear interdependence between the values of water quality variables in the LARB study regions. In addition to computing correlations across paired values of a variable X and a variable Y, non-linearity in the relationships was explored by computing correlation values for paired values of ln X and Y, of ln X and ln Y, of X and ln Y. Tables A3.17 and A3.18 in Excel File 3E on the ARBhwq CD provide a summary of the computed statistically-significant (significance level, $\alpha = 0.05$) Pearson correlation coefficient, r_P, values over the considered paired relationships between water quality variables in the USR and in the DSR, respectively. Many moderate ($0.30 \leq r_P \leq 0.60$) to strong ($r_P \geq 0.60$) correlations between the various ions are found. The interpretation of these correlations is not explored within the scope of this report, but they likely are indicative of common geological sources, weathering processes, and biogeochemical reactions (Hem 1985, Stumm and Morgan 1996). For example, Gates et al. (2009) and Bailey et al. (2012) discuss and explore relations between C_{Se}, C_U, and C_{NO_3} associated with marine shale geology, irrigation return flows, and redox chemistry.

A relationship key to the efficient measurement of salinity in a stream-aquifer system is that between TDS and EC, because EC is a relatively inexpensive and convenient means of field measurement. Least-squares regression relationships, shown in Figure 3.27, were developed between TDS and EC for surface water samples collected in the USR and the DSR. The R^2 values shown on the plots are statistically significant for $\alpha = 0.05$. The difference in the estimated relationships for the USR and DSR is likely due to the differing ion composition of the surface waters as discussed in Section *3.3.2.2.1*.

3.3.3 Groundwater Levels in the LARB Study Regions

Field data reveal that the groundwater table in the LARB study regions generally is quite shallow over the study periods. The spatial statistics of D_{wt} over all sampled groundwater monitoring well locations are summarized in Tables 3.13 and 3.14 for all sampling periods from April 1999 to August 2012 in the USR and from April 2002 to August 2012 in the DSR, respectively. Figure 3.28 shows maps of temporal-average values of D_{wt} during the irrigation season over 1999 – 2007 for the USR and 2002 – 2007 for the DSR. The values of D_{wt} in maps were generated by the groundwater models of Morway et al. (2013), which was calibrated and tested using data from the USR over 1999 – 2007 and data from the DSR over 2002 – 2007. In the USR, the overall spatiotemporal average value of D_{wt} during the irrigation season, estimated using these data-calibrated models, was 15.3 ft for the USR and 22.0 ft for the DSR.

Gates et al. (2012) and Morway et al. (2013) discuss the relation of shallow groundwater tables to irrigation practices in the LARB. Morway et al. (2013), Morway and Gates (2012), and Niemann et al (2011) discuss problems of waterlogging, salinity, and non-beneficial water consumption associated with shallow groundwater tables. The proportion of cultivated fields in the USR and DSR with D_{wt} < 6.6 ft (simulated by the models) was 24% and 21%, respectively, indicating significant susceptibility to these problems.

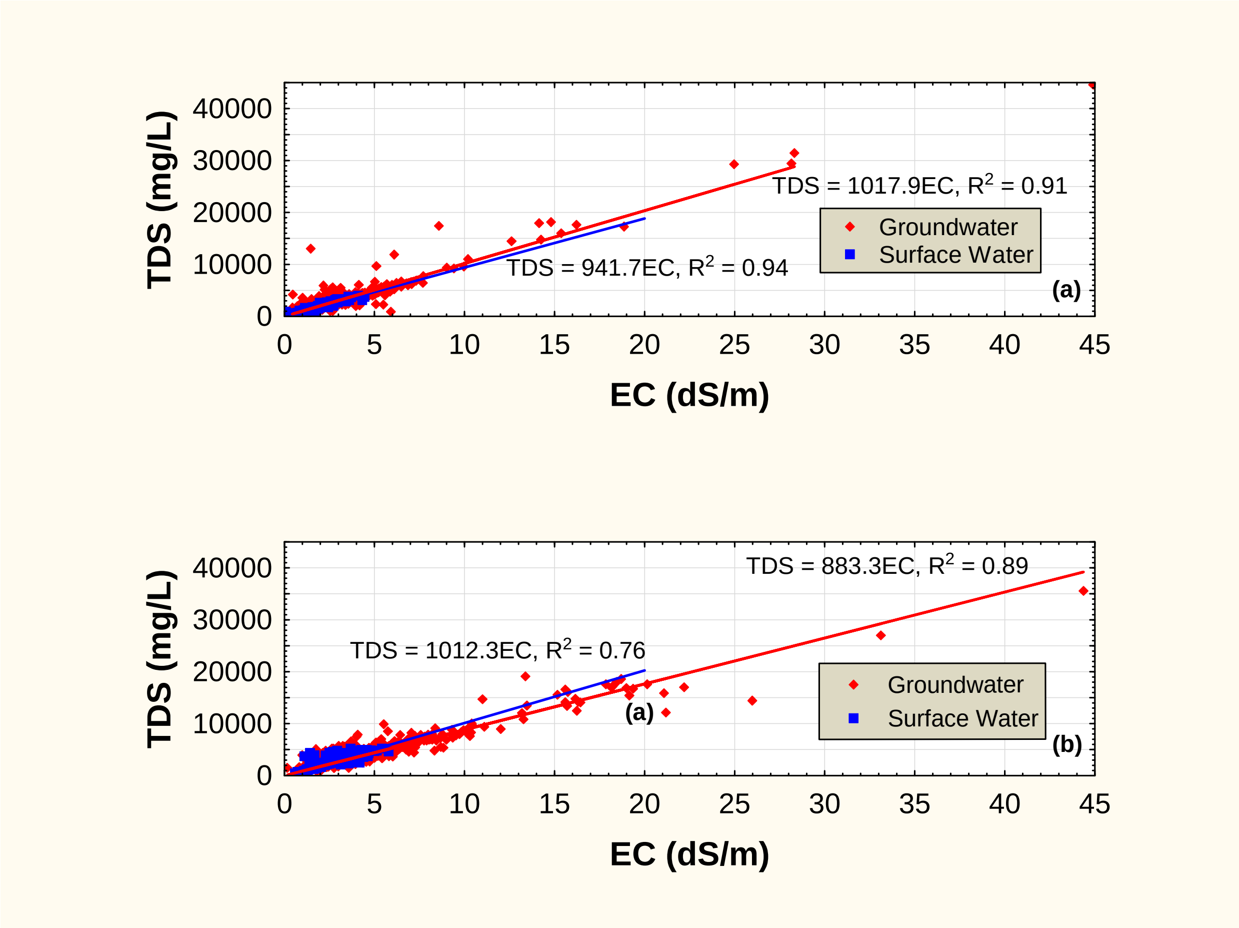


Figure 3.27. Relationship between TDS and EC in groundwater and surface water in (a) the USR and (b) the DSR.

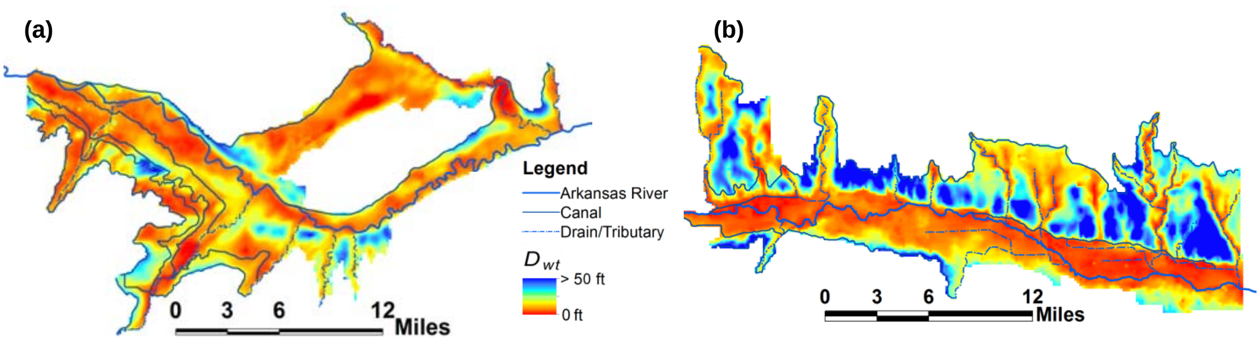


Figure 3.28. Average irrigation season D_{wt} for (a) the USR over 1999 – 2007 and (b) the DSR over 2002 – 2007, as predicted by the models of Morway et al (2013) calibrated to field data.

Substantial temporal variability occurs in measured water table depths in the monitoring wells within the USR and DSR over the study periods. Figure 3.29 shows time series plots of D_{wt} and EC for four representative monitoring wells in the USR, and Figure 3.30 presents similar plots for four representative monitoring wells in the DSR. Although there are several factors that influence water table levels, a downward trend of the water table elevation (increasing trend in D_{wt}) is seen in the plots for wells 37 and 48 in the USR and for wells 301, 361, and 372 in the DSR over 2002 – 2005, a period of severe drought when flow diversions to irrigation canals were limited. Over 2005 – 2012, as wetter conditions prevailed in the LARB, D_{wt} generally decreased in both study regions as the groundwater table rose in response to increased recharge from irrigation, canal seepage, and precipitation. Periodic seasonal fluctuations in D_{wt}, primarily in response to irrigation, are also evident in Figures 3.29 and 3.30.

Comparison of temporal variability in D_{wt} between wells within the USR may be inferred from the box-and-whisker plots in Figure 3.30. This plot shows the temporal statistics of D_{wt} for all wells having at least 100 measurements over 1999 – 2012. Similar plots are shown in Figure 3.31 for wells in the DSR over 2002 – 2012. These plots, along with values of the temporal coefficient of variation, CV_t, in D_{wt} suggest a moderate degree of variability over time within the sampled wells. Values of CV_t ranged from 0.06 to 0.85, averaging 0.29, in the USR and 0.02 to 0.62, averaging 0.17, in the DSR. The temporal 95th inter-percentile range is computed to provide an indication of the likely total fluctuation in D_{wt} over the study periods. Values of the temporal 95th inter-percentile range for the monitoring wells are between 1.5 ft and 17.8 ft, averaging 7.7 ft, in the USR. In the DSR, they are between 0.4 ft and 16.8 ft, averaging 6.8 ft. These ranges are substantial since they are equivalent to more than 50% of the average saturated thickness of the alluvial aquifer.

Table 3.13. Summary statistics of D_{wt} measured in groundwater monitoring wells in the USR.

Sampling Trip Description				D_{wt} (ft)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Readings	Average	Min	Max	CV	15th Percentile	85th Percentile
1	4/5/1999	4/7/1999	16	9	5.9	3.3	8.4	0.30	4.3	7.7
2	4/12/1999	4/15/1999	30	17	4.9	0.8	10.0	0.48	2.9	6.5
3	4/21/1999	4/21/1999	6	4	5.0	2.7	7.0	0.36	3.7	6.3
4	5/11/1999	5/13/1999	59	40	3.9	0.9	7.7	0.47	2.2	5.8
5	5/20/1999	5/27/1999	61	45	4.6	0.0	17.8	0.58	2.6	6.6
6	6/1/1999	6/4/1999	34	17	4.1	2.5	6.5	0.31	2.9	5.6
7	6/8/1999	6/11/1999	65	45	4.7	0.3	16.7	0.62	2.4	7.2
8	6/17/1999	6/18/1999	61	46	4.7	0.7	13.3	0.53	2.1	7.3
9	6/23/1999	6/24/1999	69	52	3.9	0.7	8.5	0.50	2.0	6.2
10	6/29/1999	7/1/1999	76	59	4.8	0.4	13.1	0.53	2.3	7.5
11	7/6/1999	7/8/1999	72	50	4.5	0.5	12.8	0.58	2.1	6.9
12	7/14/1999	7/17/1999	76	56	4.4	0.3	10.2	0.61	1.1	7.6
13	7/20/1999	7/23/1999	79	60	4.2	0.8	12.7	0.59	2.0	6.7
14	7/28/1999	7/30/1999	76	55	4.4	1.0	9.7	0.52	1.9	7.3
15	8/3/1999	8/5/1999	75	52	4.0	0.0	13.8	0.72	1.3	6.4
16	8/11/1999	8/14/1999	80	55	4.1	0.3	9.3	0.56	1.6	6.3
17	8/18/1999	8/19/1999	78	59	5.4	0.4	21.3	0.70	1.7	8.5
18	9/4/1999	9/4/1999	78	51	4.4	0.1	13.3	0.59	1.9	6.5
19	9/16/1999	9/17/1999	75	57	5.4	0.8	21.9	0.64	2.0	7.7
20	10/1/1999	10/6/1999	71	41	5.4	0.9	22.7	0.59	3.2	6.6
21	11/12/1999	11/13/1999	73	51	5.2	1.3	21.1	0.61	2.4	7.4
22	1/1/2000	1/5/2000	66	35	6.0	1.4	10.7	0.34	4.2	8.0
23	2/23/2000	2/24/2000	79	41	5.8	0.9	14.8	0.45	3.3	8.1
24	3/23/2000	3/26/2000	68	47	7.0	0.7	17.6	0.59	3.7	12.6
25	4/15/2000	4/15/2000	73	53	6.3	0.0	17.5	0.65	2.8	10.6
26	4/28/2000	4/29/2000	92	74	6.4	0.5	17.4	0.67	2.7	10.8
27	5/17/2000	5/19/2000	102	86	6.5	1.2	19.6	0.61	2.8	10.7
28	5/30/2000	6/2/2000	98	82	6.6	0.6	19.6	0.64	2.7	11.5
29	6/5/2000	6/8/2000	99	82	6.2	0.5	19.5	0.70	2.2	10.8
30	6/15/2000	6/17/2000	96	85	6.7	0.2	19.4	0.61	2.9	11.4
31	6/20/2000	6/24/2000	95	83	6.7	0.8	18.6	0.66	3.0	11.9
32	6/29/2000	7/1/2000	95	84	6.9	0.9	19.5	0.62	3.0	12.5
33	7/6/2000	7/8/2000	97	85	6.8	1.3	17.8	0.55	3.3	10.9
34	7/12/2000	7/14/2000	100	79	6.8	0.7	18.7	0.61	2.7	11.8
35	7/18/2000	7/21/2000	101	86	6.9	1.1	19.0	0.60	3.0	11.9
36	7/27/2000	7/31/2000	101	89	7.2	0.7	23.2	0.65	3.0	12.5
37	8/2/2000	8/4/2000	101	89	7.4	0.4	25.3	0.64	3.1	12.4
38	8/11/2000	8/12/2000	100	85	7.3	0.0	20.5	0.57	3.2	12.1

Table 3.13 (Cont.)

Sampling Trip Description				D_{wt} (ft)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Readings	Average	Min	Max	CV	15th Percentile	85th Percentile
39	8/15/2000	8/19/2000	99	75	7.6	1.6	18.1	0.51	3.7	12.3
40	9/1/2000	9/2/2000	100	87	7.8	1.2	21.3	0.56	4.1	12.7
41	9/14/2000	9/20/2000	91	73	8.2	2.0	16.2	0.42	5.2	12.7
42	9/29/2000	9/30/2000	99	74	8.1	0.3	16.5	0.49	4.1	13.5
43	10/20/2000	10/21/2000	89	69	8.0	2.2	16.6	0.50	3.5	13.9
44	12/1/2000	12/3/2000	88	69	8.4	2.5	25.8	0.56	4.1	14.0
45	1/11/2001	1/12/2001	47	26	9.8	4.3	21.2	0.47	5.6	15.3
46	1/19/2001	1/19/2001	53	35	7.5	2.9	15.1	0.45	4.4	11.6
47	3/5/2001	3/6/2001	99	55	8.8	3.1	19.0	0.47	5.0	13.8
48	3/30/2001	3/31/2001	94	61	8.1	1.0	20.8	0.54	4.3	13.4
49	4/20/2001	4/21/2001	98	73	7.9	0.0	19.6	0.58	4.0	13.5
50	5/11/2001	5/16/2001	102	86	8.0	1.4	19.6	0.54	4.0	13.4
51	5/29/2001	6/1/2001	100	81	7.4	0.8	19.6	0.60	3.5	12.8
52	6/7/2001	6/8/2001	99	85	7.5	0.8	19.8	0.59	3.7	12.5
53	6/13/2001	6/14/2001	99	84	7.5	0.1	19.8	0.62	3.6	12.1
54	6/19/2001	6/20/2001	102	86	7.2	0.8	20.6	0.61	3.2	11.8
55	6/28/2001	6/29/2001	100	85	7.6	1.2	19.4	0.56	4.1	11.9
56	7/5/2001	7/7/2001	100	85	7.6	1.4	19.4	0.57	4.2	11.9
57	7/11/2001	7/14/2001	91	73	7.5	1.5	19.7	0.53	4.8	12.1
58	7/18/2001	7/18/2001	101	85	7.6	1.0	19.2	0.56	3.9	12.3
59	7/25/2001	7/27/2001	83	65	7.2	0.9	18.6	0.54	3.8	11.7
60	7/31/2001	8/2/2001	99	82	7.7	1.0	18.3	0.53	4.2	12.2
61	8/10/2001	8/11/2001	89	77	7.6	1.3	19.1	0.52	4.4	12.3
62	8/16/2001	8/18/2001	102	85	7.6	1.4	19.4	0.52	4.3	12.5
63	9/1/2001	9/1/2001	98	78	7.8	1.2	18.2	0.48	4.5	12.4
64	9/15/2001	9/15/2001	101	76	8.0	2.1	18.1	0.44	4.8	12.4
65	9/29/2001	9/29/2001	101	68	8.1	1.6	17.5	0.47	4.4	12.9
66	10/15/2001	10/15/2001	32	21	8.1	2.5	17.4	0.51	4.1	13.2
67	10/27/2001	10/27/2001	99	62	7.8	1.9	17.5	0.54	4.0	14.1
68	11/17/2001	11/19/2001	66	39	7.4	1.9	15.2	0.46	4.1	11.2
69	1/10/2002	1/13/2002	102	56	8.7	2.6	19.6	0.49	4.7	14.1
70	2/15/2002	2/19/2002	100	59	8.2	2.3	18.8	0.52	4.5	13.2
71	3/22/2002	3/23/2002	96	60	8.4	0.0	19.4	0.52	4.6	13.6
72	4/12/2002	4/13/2002	100	63	8.0	2.1	18.3	0.50	4.4	13.1
73	5/10/2002	5/11/2002	96	55	8.5	3.0	18.3	0.47	4.7	13.5
74	5/29/2002	5/30/2002	94	59	8.5	2.7	18.3	0.45	5.3	13.9
75	6/5/2002	6/6/2002	96	55	8.7	3.0	18.4	0.45	5.2	14.3
76	6/13/2002	6/14/2002	87	52	8.8	3.1	18.4	0.44	5.5	14.3
77	6/20/2002	6/20/2002	51	21	9.9	3.9	18.5	0.46	6.2	14.9

Table 3.13 (Cont.)

Sampling Trip Description				D_{wt} (ft)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Readings	Average	Min	Max	CV	15th Percentile	85th Percentile
78	6/26/2002	6/27/2002	98	49	8.8	3.4	18.7	0.44	5.7	14.1
79	7/3/2002	7/4/2002	96	42	9.1	2.3	18.2	0.46	5.8	15.0
80	7/10/2002	7/12/2002	99	49	9.1	2.8	19.4	0.45	5.6	14.4
81	7/18/2002	7/20/2002	101	48	8.9	0.0	18.4	0.45	5.5	14.2
82	7/24/2002	7/26/2002	100	45	9.6	3.1	19.0	0.42	6.5	15.0
83	7/31/2002	8/2/2002	99	69	9.8	3.9	20.9	0.40	6.5	14.1
84	8/7/2002	8/8/2002	99	43	9.4	0.0	19.6	0.46	5.8	15.2
85	8/15/2002	8/16/2002	100	54	10.4	3.6	19.5	0.42	6.2	16.1
86	8/20/2002	8/21/2002	102	36	10.0	3.9	17.6	0.41	6.3	15.9
87	9/6/2002	9/7/2002	102	40	10.1	3.8	18.4	0.41	6.3	15.4
88	9/21/2002	9/21/2002	102	38	9.9	3.7	18.9	0.45	5.6	15.2
89	10/5/2002	10/5/2002	100	39	10.0	3.6	19.5	0.45	5.5	15.2
90	11/8/2002	11/9/2002	100	39	9.9	3.3	21.1	0.46	5.6	15.5
91	12/20/2002	12/28/2002	100	37	9.9	2.8	18.9	0.47	5.6	15.7
92	1/16/2003	1/17/2003	101	33	9.3	3.0	18.5	0.49	5.0	15.3
93	3/1/2003	3/1/2003	102	32	9.5	2.9	19.2	0.51	4.8	15.6
94	4/4/2003	4/5/2003	101	32	8.8	2.9	18.3	0.46	5.3	13.1
95	5/2/2003	5/3/2003	101	32	8.9	2.9	18.3	0.47	5.3	13.8
96	5/30/2003	5/31/2003	96	37	7.6	2.8	18.6	0.55	4.4	12.9
97	6/4/2003	6/6/2003	95	41	7.6	2.2	18.4	0.52	4.3	11.9
98	6/10/2003	6/14/2003	92	40	7.5	2.0	18.1	0.53	4.0	12.2
99	6/19/2003	6/20/2003	91	34	7.4	1.5	18.2	0.55	4.1	12.1
100	7/2/2003	7/4/2003	92	40	7.6	1.5	18.2	0.51	4.3	12.6
101	7/8/2003	7/13/2003	94	42	7.3	2.1	17.2	0.48	4.5	10.6
102	7/17/2003	7/20/2003	81	45	8.3	2.4	19.1	0.51	4.9	13.5
103	7/24/2003	7/27/2003	95	40	8.6	2.5	18.1	0.49	5.1	13.9
104	7/31/2003	8/2/2003	95	42	8.6	2.5	19.0	0.49	5.5	14.0
105	8/14/2003	8/16/2003	92	38	9.7	3.2	19.0	0.45	6.0	15.2
106	8/20/2003	8/20/2003	92	40	9.3	3.4	19.2	0.45	6.3	14.9
107	9/5/2003	9/6/2003	84	41	9.1	3.9	18.4	0.41	6.3	13.8
108	10/10/2003	10/11/2003	99	40	9.8	2.9	22.6	0.47	5.5	14.2
109	11/15/2003	11/15/2003	99	41	9.0	3.1	21.2	0.46	5.7	14.1
110	12/22/2003	12/24/2003	100	38	9.0	2.9	21.0	0.48	5.2	14.3
111	1/13/2004	1/16/2004	94	34	9.2	2.9	21.4	0.47	5.8	14.1
112	2/13/2004	2/14/2004	96	39	8.8	2.9	16.7	0.42	5.4	13.7
113	3/18/2004	3/19/2004	61	28	9.0	2.8	16.2	0.40	6.2	13.0
114	4/23/2004	4/24/2004	90	39	10.1	2.1	20.0	0.45	5.1	15.2
115	5/3/2004	5/5/2004	79	47	9.4	2.7	19.8	0.50	4.6	15.2
116	5/17/2004	5/18/2004	92	57	9.5	2.8	31.2	0.55	4.4	14.1

Table 3.13 (Cont.)

Sampling Trip Description				D_{wt} (ft)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Readings	Average	Min	Max	CV	15th Percentile	85th Percentile
117	5/24/2004	5/25/2004	96	60	9.4	2.9	20.7	0.47	5.3	13.7
118	6/7/2004	6/10/2004	93	61	8.9	2.6	18.5	0.49	4.4	13.3
119	6/14/2004	6/17/2004	88	56	9.2	0.9	18.9	0.52	3.9	14.4
120	6/28/2004	6/29/2004	92	63	9.3	1.5	24.7	0.52	4.6	15.2
121	7/5/2004	7/6/2004	89	61	9.3	1.4	19.2	0.50	4.3	15.4
122	7/12/2004	7/14/2004	96	76	11.3	1.5	35.3	0.65	4.9	17.4
123	7/19/2004	7/20/2004	100	79	12.0	1.4	36.2	0.62	5.1	18.0
124	7/25/2004	7/27/2004	100	81	11.3	1.2	36.1	0.61	4.7	17.3
125	8/2/2004	8/3/2004	102	86	12.0	1.3	35.7	0.64	4.9	18.4
126	8/9/2004	8/10/2004	101	83	12.0	1.2	35.0	0.62	5.2	18.9
127	8/16/2004	8/18/2004	103	85	12.1	0.9	35.1	0.63	5.2	19.0
128	8/31/2004	9/1/2004	82	67	13.5	1.0	41.9	0.62	5.7	19.7
129	9/18/2004	9/18/2004	99	86	12.8	1.5	44.2	0.62	5.6	19.1
130	10/22/2004	10/23/2004	103	79	13.0	1.6	35.7	0.59	6.0	20.5
131	11/22/2004	11/23/2004	96	82	12.8	1.6	37.1	0.61	5.4	19.7
132	12/20/2004	12/21/2004	101	78	12.4	1.0	35.9	0.61	5.3	17.9
133	1/11/2005	1/14/2005	103	82	12.8	2.7	33.6	0.61	5.7	20.0
134	2/13/2005	2/19/2005	101	82	13.0	2.8	36.0	0.60	5.7	20.3
135	3/15/2005	3/17/2005	102	79	12.7	3.0	38.3	0.60	5.9	18.7
136	4/9/2005	4/16/2005	102	80	12.3	2.0	36.6	0.64	5.3	20.3
137	5/13/2005	5/17/2005	102	80	12.3	1.6	34.4	0.63	5.2	17.7
138	6/6/2005	6/8/2005	103	78	11.2	0.8	34.1	0.68	4.4	17.3
139	6/13/2005	6/15/2005	104	85	11.1	1.0	34.4	0.67	4.4	16.5
140	6/20/2005	6/23/2005	97	80	11.7	0.7	34.9	0.66	4.8	17.6
141	6/28/2005	6/29/2005	92	79	10.8	0.8	32.7	0.61	4.8	16.0
142	7/5/2005	7/6/2005	102	85	11.2	0.7	35.0	0.68	4.3	16.7
143	7/11/2005	7/13/2005	107	90	11.6	1.0	34.9	0.64	4.8	17.9
144	7/19/2005	7/21/2005	98	80	11.3	0.9	35.3	0.66	5.0	16.6
145	7/24/2005	7/28/2005	41	31	13.6	2.7	35.6	0.61	6.3	21.1
146	8/1/2005	8/5/2005	61	55	10.6	0.9	35.7	0.62	4.4	15.7
147	8/15/2005	8/18/2005	101	81	11.8	0.7	35.7	0.65	5.0	18.4
148	9/24/2005	9/24/2005	89	72	13.2	1.4	34.6	0.57	6.2	19.3
149	10/21/2005	10/22/2005	103	84	12.8	2.0	33.4	0.59	5.7	19.0
150	11/21/2005	11/23/2005	102	84	13.0	2.4	33.3	0.57	5.9	19.5
151	12/19/2005	12/22/2005	101	86	12.9	2.9	33.1	0.57	5.6	19.3
152	1/10/2006	1/13/2006	95	76	13.1	2.9	33.1	0.58	5.9	19.6
153	2/9/2006	2/12/2006	100	79	12.9	3.1	33.1	0.58	5.9	19.6
154	3/13/2006	3/15/2006	103	87	12.9	3.0	41.9	0.59	5.9	19.0
155	5/22/2006	5/25/2006	90	81	12.1	2.8	35.3	0.63	5.1	18.4

Table 3.13 (Cont.)

Sampling Trip Description				D_{wt} (ft)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Readings	Average	Min	Max	CV	15th Percentile	85th Percentile
156	5/29/2006	5/30/2006	95	80	11.9	0.0	35.7	0.66	4.9	18.3
157	6/12/2006	6/15/2006	103	82	11.2	1.5	35.6	0.64	4.5	17.4
158	6/17/2006	6/20/2006	148	125	11.6	1.6	35.4	0.63	4.9	17.6
159	6/26/2006	6/27/2006	46	40	11.5	1.2	33.6	0.60	4.8	16.9
160	7/3/2006	7/6/2006	97	80	11.8	1.2	35.3	0.63	4.8	18.1
161	7/11/2006	7/13/2006	96	76	11.3	0.7	35.6	0.64	4.1	17.6
162	7/17/2006	7/19/2006	96	81	11.4	0.9	35.8	0.65	4.5	17.5
163	7/31/2006	8/1/2006	12	11	7.4	4.5	13.8	0.39	5.0	10.0
164	8/14/2006	8/16/2006	97	67	12.1	1.1	34.6	0.57	5.0	17.7
165	9/21/2006	9/22/2006	96	79	11.8	1.1	32.9	0.64	4.6	18.4
166	11/4/2006	11/5/2006	102	79	11.5	1.0	33.6	0.68	4.2	18.6
167	12/17/2006	12/18/2006	102	79	12.3	2.6	32.9	0.58	5.3	18.9
168	2/27/2007	3/1/2007	95	36	12.9	2.0	32.1	0.63	4.7	19.6
169	4/23/2007	4/25/2007	62	40	12.1	2.5	33.2	0.69	5.2	20.5
170	5/21/2007	5/24/2007	154	118	10.1	1.5	33.2	0.70	3.9	17.1
171	6/4/2007	6/6/2007	75	55	11.2	1.9	33.3	0.69	4.5	17.9
172	6/26/2007	6/28/2007	104	65	10.5	0.4	33.8	0.69	4.2	16.7
173	7/3/2007	7/6/2007	102	75	10.2	0.8	34.8	0.70	3.9	15.8
174	7/19/2007	7/21/2007	105	73	10.4	0.9	34.7	0.68	4.3	15.5
175	10/6/2007	10/7/2007	52	39	9.9	2.6	30.8	0.65	5.1	14.2
176	12/16/2007	12/18/2007	105	62	10.9	2.7	32.6	0.61	5.1	16.4
177	1/18/2008	1/20/2008	95	74	11.8	3.1	34.6	0.62	5.7	16.7
178	3/17/2008	3/22/2008	52	35	10.7	4.3	34.1	0.64	5.6	15.8
179	4/19/2008	4/20/2008	106	80	10.3	2.7	33.1	0.66	4.4	16.4
180	5/27/2008	5/28/2008	69	35	9.0	1.6	20.1	0.56	4.1	14.5
181	6/21/2008	6/25/2008	193	137	9.9	-1.5	35.4	0.67	4.3	16.0
182	7/2/2008	7/3/2008	102	64	9.7	1.1	38.0	0.69	3.8	15.9
183	7/9/2008	7/9/2008	62	37	9.7	2.2	35.1	0.65	4.5	14.4
184	8/14/2008	8/15/2008	57	42	8.6	2.3	31.8	0.65	4.3	12.5
185	1/15/2009	1/16/2009	51	33	10.2	4.3	32.5	0.65	4.9	15.6
186	2/5/2009	2/5/2009	14	10	8.0	3.0	14.4	0.51	3.9	12.9
187	5/13/2009	5/14/2009	52	35	9.5	2.9	27.1	0.64	4.0	15.7
188	5/20/2009	5/21/2009	100	50	8.3	0.1	24.2	0.65	3.8	14.9
189	6/23/2009	6/24/2009	91	46	8.4	-0.3	22.0	0.66	3.3	15.4
190	7/21/2009	7/23/2009	51	36	7.8	0.2	23.7	0.65	4.0	12.0
191	8/11/2009	8/12/2009	98	44	8.4	-0.3	22.0	0.68	3.0	15.4
192	10/1/2009	10/2/2009	94	47	10.2	-0.3	35.4	0.66	4.2	17.6
193	11/19/2009	11/20/2009	51	34	8.7	3.4	26.4	0.62	4.9	12.2
194	1/2/2010	1/3/2010	102	52	10.5	1.8	32.2	0.64	5.1	17.6

Table 3.13 (Cont.)

Sampling Trip Description				D_{wt} (ft)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Readings	Average	Min	Max	CV	15th Percentile	85th Percentile
195	3/12/2010	3/18/2010	152	89	10.8	1.9	34.5	0.61	5.4	17.9
196	5/14/2010	5/16/2010	39	33	10.2	3.7	27.8	0.58	5.7	15.9
197	5/24/2010	5/25/2010	103	56	11.0	3.2	35.5	0.65	4.7	17.4
198	6/14/2010	6/15/2010	103	69	10.1	0.7	32.8	0.67	4.4	16.4
199	7/15/2010	7/16/2010	101	66	9.8	2.6	27.6	0.52	4.9	15.3
200	7/20/2010	7/21/2010	50	37	8.4	0.8	22.7	0.65	4.3	13.0
201	8/10/2010	8/13/2010	146	95	9.5	1.9	32.3	0.60	4.3	15.1
202	11/26/2010	11/27/2010	101	67	10.6	3.4	33.0	0.60	4.9	16.7
203	1/4/2011	1/5/2011	104	69	9.9	1.0	32.9	0.67	4.4	16.4
204	3/15/2011	3/16/2011	76	46	11.3	2.1	33.4	0.63	5.7	17.8
205	5/20/2011	5/21/2011	36	26	9.2	3.4	28.1	0.64	4.4	12.6
206	5/30/2011	6/1/2011	95	52	9.0	1.0	21.5	0.57	3.7	15.0
207	6/20/2011	6/21/2011	104	55	8.9	0.9	21.4	0.57	3.4	14.5
208	7/24/2011	7/25/2011	90	48	9.5	1.0	31.5	0.64	3.4	14.8
209	8/16/2011	8/19/2011	106	54	9.0	0.9	21.4	0.55	3.9	14.9
210	11/25/2011	11/26/2011	104	54	9.9	1.2	21.1	0.53	4.9	16.9
211	1/9/2012	1/11/2012	103	38	8.9	2.5	20.7	0.55	3.9	15.1
212	3/13/2012	3/14/2012	104	54	9.6	1.2	21.2	0.54	4.8	15.4
213	5/21/2012	5/22/2012	104	52	9.7	1.3	21.5	0.54	4.9	16.6
214	6/7/2012	6/7/2012	13	11	7.5	3.1	13.3	0.44	4.2	10.9
215	6/16/2012	6/18/2012	102	56	10.7	2.6	32.0	0.52	5.3	15.7
216	7/21/2012	7/22/2012	102	52	11.2	2.8	32.1	0.55	5.7	16.2
217	8/13/2012	8/14/2012	103	51	12.9	4.1	31.6	0.43	7.4	18.1

Table 3.14. Summary statistics of D_{wt} measured in groundwater monitoring wells in the DSR.

Sampling Trip Description				D_{wt} (ft)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Readings	Average	Min	Max	CV	15th Percentile	85th Percentile
1	4/12/2002	4/14/2002	85	59	9.4	1.5	20.7	0.48	4.9	13.9
2	5/1/2002	5/2/2002	90	61	9.5	1.2	21.2	0.50	5.5	14.9
3	5/14/2002	5/17/2002	91	67	9.7	2.0	21.3	0.50	5.2	14.8
4	5/29/2002	5/31/2002	104	71	10.5	2.5	22.5	0.50	5.0	17.1
5	6/5/2002	6/6/2002	102	69	10.4	2.7	23.4	0.48	5.6	16.2
6	6/13/2002	6/14/2002	104	69	9.9	2.9	22.6	0.50	5.2	15.6
7	6/19/2002	6/20/2002	105	68	9.8	3.0	22.7	0.50	5.1	15.3
8	6/26/2002	6/27/2002	103	63	10.0	3.0	22.4	0.50	5.2	15.8
9	7/2/2002	7/5/2002	106	65	9.9	3.2	22.7	0.52	5.0	16.4
10	7/10/2002	7/12/2002	105	64	9.9	3.3	23.1	0.51	4.8	16.0
11	7/17/2002	7/18/2002	103	64	9.6	3.5	23.1	0.49	5.1	15.4
12	7/24/2002	7/24/2002	107	62	9.8	3.3	23.3	0.49	5.1	15.8
13	7/31/2002	8/1/2002	106	57	9.8	3.3	23.5	0.51	4.8	16.1
14	8/8/2002	8/8/2002	105	59	9.9	3.4	23.8	0.49	5.6	15.7
15	8/14/2002	8/14/2002	105	57	10.0	3.4	23.7	0.50	5.1	16.5
16	8/29/2002	8/29/2002	111	57	10.4	3.3	23.9	0.50	5.8	17.2
17	9/6/2002	9/7/2002	111	45	10.9	3.2	22.9	0.51	5.6	18.1
18	9/21/2002	9/22/2002	117	65	11.0	3.2	28.9	0.54	5.3	18.5
19	9/27/2002	9/28/2002	116	64	10.7	3.4	29.0	0.55	5.5	18.4
20	11/5/2002	11/5/2002	117	64	10.5	2.9	29.5	0.57	5.3	18.4
21	12/20/2002	12/21/2002	83	47	9.9	3.1	29.6	0.58	5.7	15.4
22	12/27/2002	12/27/2002	33	10	10.8	3.2	23.2	0.68	4.8	19.2
23	1/15/2003	1/15/2003	105	63	10.9	3.0	29.9	0.57	5.8	19.3
24	2/22/2003	2/22/2003	107	64	11.0	3.1	30.1	0.55	6.2	18.8
25	3/21/2003	3/22/2003	110	75	12.1	3.1	31.4	0.56	6.2	19.2
26	4/18/2003	4/19/2003	102	68	12.2	3.3	30.3	0.55	6.6	20.2
27	4/25/2003	5/4/2003	50	45	13.1	3.7	30.5	0.54	7.1	20.9
28	5/16/2003	5/17/2003	108	75	12.4	3.8	30.7	0.56	6.0	20.3
29	5/29/2003	5/30/2003	126	91	12.4	3.0	30.8	0.55	5.9	20.6
30	6/3/2003	6/6/2003	119	80	12.6	3.1	30.7	0.55	6.2	20.2
31	6/10/2003	6/13/2003	130	98	12.2	2.9	30.6	0.56	5.9	20.2
32	6/19/2003	6/20/2003	73	55	10.2	2.9	30.4	0.61	5.0	15.9
33	6/30/2003	7/3/2003	138	105	11.8	2.8	29.4	0.54	6.0	20.1
34	7/7/2003	7/8/2003	129	99	12.9	2.8	31.3	0.55	6.3	20.6
35	7/10/2003	7/11/2003	103	81	12.3	3.1	30.3	0.53	6.0	20.5
36	7/17/2003	7/17/2003	109	77	12.4	3.0	30.3	0.52	6.2	20.1
37	7/24/2003	7/25/2003	105	75	12.9	3.1	30.6	0.51	7.1	20.9

Table 3.14 (Cont.)

Sampling Trip Description				D_{wt} (ft)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Readings	Average	Min	Max	CV	15th Percentile	85th Percentile
38	7/27/2003	7/31/2003	159	123	12.9	3.2	30.7	0.52	6.7	21.1
39	8/7/2003	8/7/2003	108	79	12.9	3.5	30.9	0.52	6.4	20.8
40	8/13/2003	8/15/2003	106	73	13.2	3.2	31.1	0.48	7.4	20.5
41	8/19/2003	8/20/2003	111	85	13.3	3.2	30.9	0.52	6.7	21.5
42	9/5/2003	9/6/2003	109	82	13.5	3.1	31.0	0.52	6.8	21.5
43	9/19/2003	9/21/2003	105	76	13.7	3.6	31.1	0.53	6.1	22.1
44	10/18/2003	10/18/2003	106	74	14.1	3.2	31.5	0.52	7.2	22.4
45	10/25/2003	11/2/2003	50	45	14.6	3.5	31.7	0.52	7.5	23.2
46	11/21/2003	11/28/2003	111	76	13.7	3.1	31.6	0.53	7.2	22.1
47	1/12/2004	1/17/2004	163	116	13.9	3.2	31.9	0.52	7.3	22.3
48	2/24/2004	2/26/2004	110	72	13.8	3.3	31.7	0.54	7.1	22.3
49	3/15/2004	3/19/2004	162	118	14.1	3.5	31.5	0.53	7.2	22.7
50	4/23/2004	4/24/2004	105	54	12.5	1.8	26.9	0.54	4.5	21.6
51	4/30/2004	5/6/2004	162	120	13.7	0.2	32.4	0.56	6.3	22.6
52	5/17/2004	5/17/2004	108	76	13.5	3.2	32.5	0.54	6.2	21.7
53	5/27/2004	5/28/2004	109	74	13.4	2.8	31.1	0.53	6.5	21.7
54	6/1/2004	6/4/2004	54	49	14.2	3.4	31.9	0.52	7.0	22.7
55	6/9/2004	6/10/2004	105	68	13.0	3.1	32.1	0.56	6.0	21.4
56	6/17/2004	6/18/2004	109	62	13.3	3.1	32.0	0.55	6.2	22.1
57	6/23/2004	6/24/2004	111	70	12.4	1.5	31.9	0.61	5.0	21.0
58	6/28/2004	7/1/2004	163	108	13.0	2.5	31.9	0.56	5.5	21.5
59	7/8/2004	7/9/2004	108	67	12.7	2.8	31.9	0.57	5.7	21.4
60	7/20/2004	7/23/2004	105	74	13.0	3.0	31.6	0.55	6.1	21.5
61	7/29/2004	7/30/2004	111	73	13.4	1.2	34.3	0.60	5.7	22.3
62	8/2/2004	8/6/2004	163	128	13.3	1.2	32.8	0.57	6.0	21.9
63	8/11/2004	8/12/2004	111	65	12.2	1.3	32.5	0.61	5.9	20.7
64	8/18/2004	8/20/2004	110	76	13.1	1.4	32.1	0.59	6.2	21.9
65	8/31/2004	9/1/2004	108	82	13.3	1.2	31.6	0.60	5.9	21.7
66	9/18/2004	9/19/2004	109	76	13.7	2.4	32.0	0.55	6.5	21.5
67	10/16/2004	10/16/2004	109	80	13.2	2.8	32.0	0.57	5.7	21.3
68	11/4/2004	11/8/2004	54	51	13.8	3.0	31.9	0.55	6.8	22.1
69	11/26/2004	11/26/2004	107	67	13.2	3.0	31.3	0.57	6.5	21.7
70	12/23/2004	12/26/2004	106	64	14.2	3.1	32.0	0.55	6.8	22.2
71	1/10/2005	1/17/2005	165	125	13.8	3.0	32.1	0.56	6.7	22.5
72	2/26/2005	2/28/2005	107	73	13.7	1.3	32.9	0.57	6.6	22.3
73	3/15/2005	3/20/2005	164	125	13.8	3.1	33.9	0.56	6.5	22.3
74	4/16/2005	4/17/2005	113	71	13.3	3.2	30.7	0.54	6.5	21.9
75	5/6/2005	5/17/2005	109	85	13.0	2.8	32.3	0.62	5.5	21.9
76	5/23/2005	5/27/2005	105	64	13.7	2.3	31.9	0.60	5.5	21.9
77	6/2/2005	6/5/2005	111	75	12.5	1.6	31.5	0.65	5.5	21.4

Table 3.14 (Cont.)

Sampling Trip Description				D_{wt} (ft)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Readings	Average	Min	Max	CV	15th Percentile	85th Percentile
78	6/9/2005	6/11/2005	110	78	12.7	1.4	31.4	0.62	5.7	21.1
79	6/23/2005	6/23/2005	108	81	12.1	1.0	30.8	0.62	5.2	20.2
80	6/27/2005	7/2/2005	164	132	12.2	1.0	30.5	0.61	5.4	21.2
81	7/8/2005	7/9/2005	111	86	12.4	1.0	30.3	0.64	5.0	22.3
82	7/13/2005	7/15/2005	109	85	12.0	1.3	30.4	0.62	5.4	20.2
83	7/19/2005	7/23/2005	165	133	12.3	1.6	30.4	0.60	5.3	20.9
84	7/28/2005	7/29/2005	109	85	12.4	1.8	31.9	0.60	5.6	20.5
85	8/4/2005	8/4/2005	111	85	12.7	2.7	30.7	0.59	6.2	21.5
86	8/11/2005	8/19/2005	165	129	12.9	2.7	30.7	0.54	6.6	21.1
87	9/16/2005	9/16/2005	111	86	13.5	3.0	31.0	0.54	6.7	21.7
88	10/14/2005	10/14/2005	107	79	13.5	2.3	31.2	0.57	6.7	22.0
89	11/18/2005	11/22/2005	166	124	13.7	2.9	31.7	0.55	6.9	22.5
90	12/21/2005	12/23/2005	111	74	14.2	2.9	32.7	0.56	6.9	23.0
91	1/10/2006	1/13/2006	59	42	13.2	2.8	30.9	0.55	6.8	22.5
92	1/22/2006	1/24/2006	104	68	14.6	2.9	33.0	0.55	7.1	23.4
93	2/20/2006	2/21/2006	103	68	14.3	3.0	33.8	0.56	7.0	23.6
94	3/11/2006	3/15/2006	167	116	14.1	2.9	33.8	0.53	7.3	23.3
95	4/22/2006	4/22/2006	103	74	13.9	3.0	34.5	0.56	6.9	22.7
96	5/13/2006	5/16/2006	60	44	13.4	3.0	29.9	0.51	7.3	20.4
97	5/22/2006	5/24/2006	112	72	14.1	3.3	32.6	0.54	7.3	23.1
98	5/30/2006	5/31/2006	111	65	14.0	3.0	35.3	0.56	7.4	22.5
99	6/5/2006	6/9/2006	87	56	13.8	3.7	36.3	0.60	6.8	22.2
100	6/12/2006	6/15/2006	167	119	13.6	2.6	36.5	0.55	6.6	22.0
101	6/21/2006	6/22/2006	107	66	13.6	2.8	32.4	0.57	6.3	21.8
102	6/26/2006	6/27/2006	109	61	13.6	2.4	32.4	0.58	6.3	21.8
103	7/3/2006	7/4/2006	110	67	12.4	2.4	36.6	0.63	5.8	20.7
104	7/11/2006	7/13/2006	169	123	13.0	1.7	34.6	0.60	5.7	21.8
105	7/17/2006	7/18/2006	108	69	12.8	1.3	34.1	0.64	5.6	21.6
106	7/31/2006	8/3/2006	106	71	13.2	2.0	33.1	0.61	5.7	21.9
107	8/7/2006	8/10/2006	164	117	13.7	2.4	33.2	0.54	6.3	22.1
108	10/7/2006	10/8/2006	119	76	12.3	1.2	33.2	0.63	5.6	20.1
109	11/10/2006	11/11/2006	97	60	12.4	2.1	32.3	0.64	5.2	20.4
110	11/18/2006	11/20/2006	61	53	12.6	2.3	32.2	0.56	6.4	20.0
111	12/9/2006	12/10/2006	105	57	12.2	2.3	31.9	0.64	5.4	20.2
112	2/19/2007	2/20/2007	24	16	12.4	2.4	32.5	0.70	5.2	18.8
113	3/10/2007	3/11/2007	61	38	10.7	1.2	28.5	0.67	3.9	19.2
114	3/20/2007	3/21/2007	110	70	11.7	1.3	32.5	0.70	4.7	21.5
115	4/17/2007	4/18/2007	107	60	11.9	0.8	32.4	0.66	5.0	21.0
116	5/15/2007	5/18/2007	171	109	10.6	1.0	31.0	0.62	4.7	17.5
117	5/29/2007	5/30/2007	108	70	10.0	1.1	31.8	0.65	4.8	17.1

Table 3.14 (Cont.)

Sampling Trip Description				D_{wt} (ft)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Readings	Average	Min	Max	CV	15th Percentile	85th Percentile
118	6/12/2007	6/15/2007	110	57	10.4	1.0	32.4	0.69	4.4	18.5
119	6/19/2007	6/22/2007	172	122	10.7	1.0	34.2	0.67	4.4	18.5
120	6/25/2007	6/26/2007	110	65	11.2	0.8	34.1	0.74	4.2	19.2
121	7/2/2007	7/3/2007	108	67	10.8	0.5	32.7	0.71	4.4	17.6
122	7/10/2007	7/11/2007	99	59	10.0	0.4	32.7	0.70	4.2	17.1
123	7/17/2007	7/20/2007	147	85	11.2	0.3	30.7	0.68	4.4	19.2
124	7/22/2007	7/24/2007	166	108	10.1	0.6	30.1	0.62	4.6	16.5
125	7/30/2007	7/31/2007	86	52	10.7	0.8	39.1	0.72	4.1	17.3
126	8/13/2007	8/15/2007	88	62	9.6	2.9	29.3	0.55	4.9	15.2
127	10/7/2007	10/8/2007	54	36	15.3	4.2	33.2	0.58	5.8	23.9
128	10/13/2007	10/13/2007	98	58	9.8	1.4	31.0	0.61	4.9	14.9
129	11/17/2007	11/19/2007	60	47	11.6	3.0	30.2	0.52	6.1	17.7
130	11/21/2007	11/23/2007	112	62	11.1	1.7	31.3	0.57	6.0	16.4
131	12/26/2007	12/27/2007	98	55	11.2	2.1	31.3	0.57	5.6	16.9
132	1/15/2008	1/17/2008	61	43	11.6	3.1	30.7	0.49	6.6	17.1
133	2/16/2008	2/16/2008	29	20	10.5	5.0	29.9	0.56	6.8	14.4
134	3/18/2008	3/19/2008	107	53	10.8	1.8	31.3	0.57	5.3	17.2
135	4/19/2008	4/20/2008	102	49	10.7	1.7	31.2	0.59	5.2	16.9
136	5/20/2008	5/21/2008	59	42	11.3	2.6	26.9	0.52	6.0	17.4
137	5/26/2008	5/26/2008	104	69	12.3	1.7	30.0	0.57	5.8	19.4
138	6/14/2008	6/16/2008	105	66	11.8	1.7	30.6	0.59	5.2	19.6
139	6/25/2008	6/26/2008	113	71	11.3	0.9	29.0	0.57	5.6	17.4
140	7/1/2008	7/2/2008	114	73	11.0	1.0	29.1	0.62	4.7	19.4
141	7/7/2008	7/8/2008	112	73	11.2	1.0	30.9	0.64	4.7	19.4
142	7/12/2008	7/16/2008	46	35	12.1	1.2	29.0	0.65	5.0	21.0
143	7/22/2008	7/23/2008	115	77	10.8	1.0	30.2	0.62	4.6	18.3
144	7/28/2008	7/29/2008	115	71	10.8	1.1	30.6	0.62	4.8	17.1
145	8/5/2008	8/6/2008	116	71	10.2	1.1	31.6	0.62	4.8	15.8
146	11/20/2008	11/20/2008	61	45	12.0	4.1	28.7	0.50	6.2	17.9
147	12/23/2008	12/24/2008	112	55	10.2	3.2	28.5	0.55	5.2	16.0
148	1/17/2009	1/18/2009	107	45	11.5	3.4	28.8	0.54	5.8	17.9
149	3/13/2009	3/14/2009	61	38	12.3	3.0	31.1	0.52	5.6	18.7
150	5/27/2009	5/28/2009	74	42	11.6	3.2	28.3	0.54	5.7	17.6
151	6/16/2009	6/16/2009	24	9	8.8	3.6	19.0	0.54	5.1	12.5
152	6/24/2009	6/25/2009	61	41	12.5	2.5	29.2	0.49	5.1	18.3
153	7/7/2009	7/8/2009	114	67	10.4	0.4	28.1	0.64	4.7	16.1
154	7/23/2009	7/24/2009	106	53	9.8	0.4	28.3	0.60	4.4	15.7
155	8/9/2009	8/10/2009	136	68	9.5	0.4	29.6	0.57	4.4	14.4
156	8/27/2009	8/29/2009	60	34	11.3	2.1	29.7	0.59	5.4	18.9
157	10/15/2009	10/15/2009	69	30	11.2	0.5	27.6	0.61	4.1	18.3

Table 3.14 (Cont.)

Sampling Trip Description				D_{wt} (ft)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Readings	Average	Min	Max	CV	15th Percentile	85th Percentile
158	1/3/2010	1/7/2010	167	88	11.4	1.9	32.5	0.57	5.0	17.8
159	3/13/2010	3/16/2010	167	95	11.9	1.9	31.1	0.57	5.3	19.8
160	5/17/2010	5/18/2010	110	57	10.6	0.7	31.5	0.59	4.2	16.7
161	6/8/2010	6/9/2010	48	23	13.3	4.3	29.2	0.53	6.0	20.7
162	6/22/2010	6/23/2010	108	65	10.9	0.6	29.6	0.59	4.8	17.8
163	7/13/2010	7/14/2010	110	56	10.6	1.5	27.7	0.61	4.3	17.7
164	8/10/2010	8/11/2010	148	89	11.2	1.5	29.6	0.60	4.9	19.1
165	11/23/2010	11/24/2010	112	59	11.8	2.7	28.7	0.54	5.9	18.0
166	1/2/2011	1/3/2011	111	63	11.7	2.6	29.7	0.54	5.7	18.4
167	3/12/2011	3/13/2011	108	48	11.8	2.4	30.1	0.58	5.7	19.6
168	5/18/2011	5/19/2011	48	33	12.1	3.6	27.3	0.53	6.2	19.7
169	5/27/2011	5/28/2011	109	50	11.0	2.3	30.2	0.56	5.7	17.0
170	7/22/2011	7/23/2011	109	53	11.5	2.2	29.8	0.57	5.7	18.8
171	8/18/2011	8/19/2011	110	43	11.8	2.2	27.8	0.51	6.3	18.4
172	11/23/2011	11/25/2011	108	46	11.0	2.2	29.6	0.57	5.5	18.9
173	1/5/2012	1/8/2012	110	31	12.6	3.9	22.5	0.44	7.0	19.1
174	3/10/2012	3/12/2012	111	47	12.2	3.9	30.6	0.56	6.2	19.1
175	5/14/2012	5/16/2012	109	44	12.3	4.2	30.8	0.55	6.8	19.4
176	6/17/2012	6/18/2012	111	45	12.9	5.1	28.9	0.48	6.9	19.8
177	7/21/2012	7/21/2012	112	43	14.8	5.0	51.2	0.60	7.1	21.8
178	8/14/2012	8/14/2012	83	32	14.1	5.8	32.6	0.50	7.9	19.5

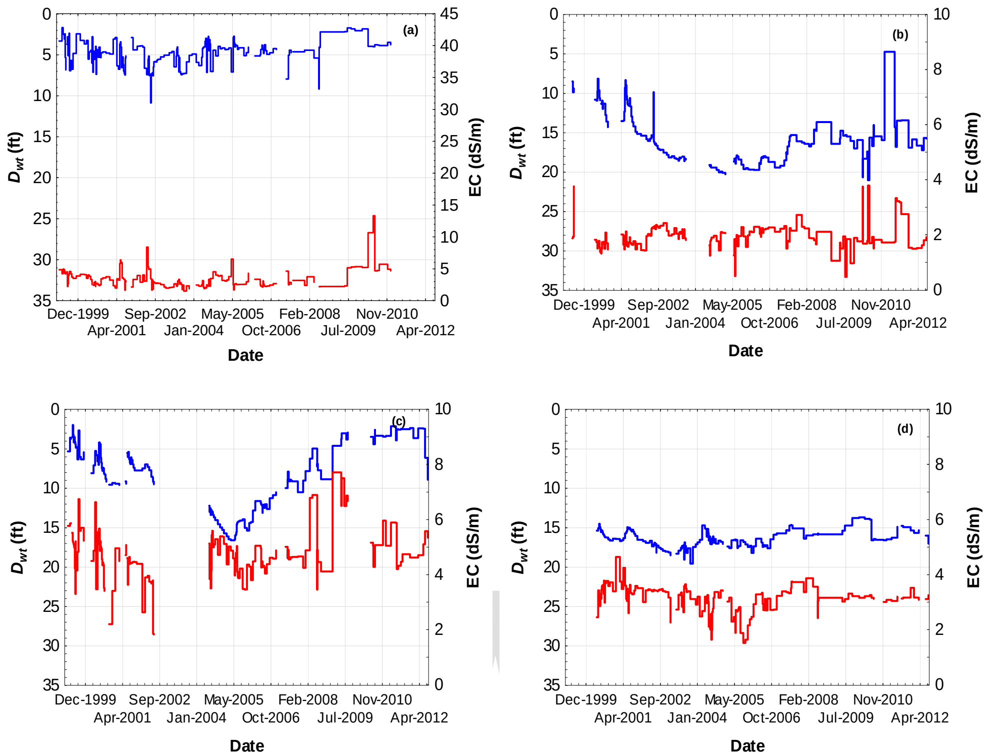


Figure 3.29. Example time series plots of D_{wt} (blue line) and EC (red line), as measured in the USR in groundwater monitoring well numbers (a) 7, (b) 37, (c) 48, and (d) 85.

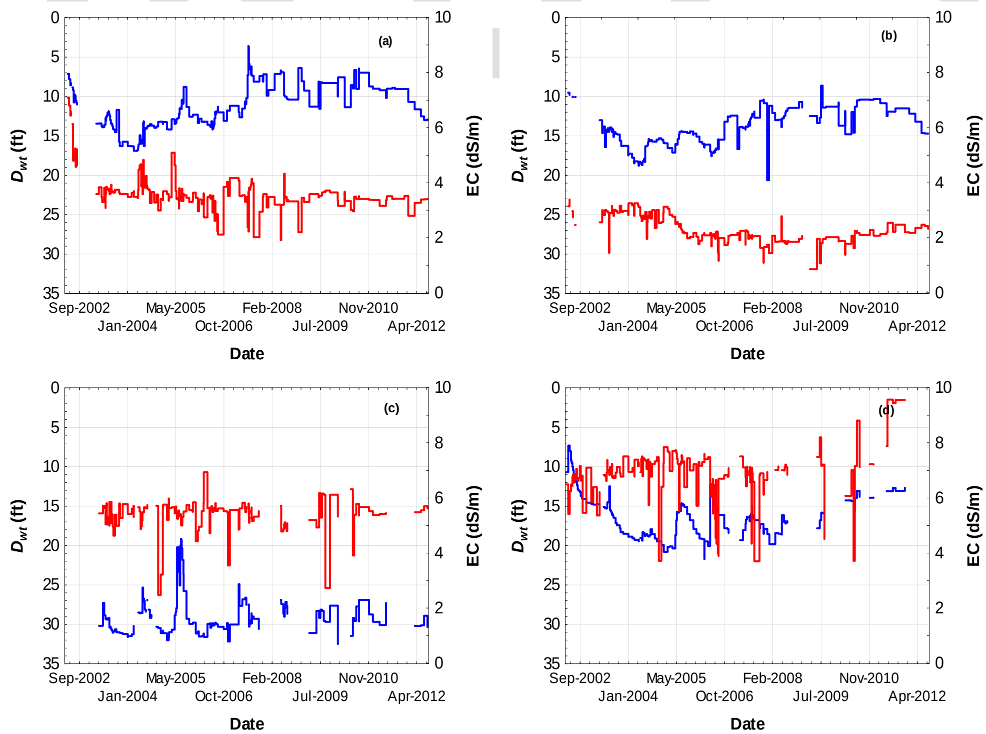


Figure 3.30. Example time series plots of D_{wt} (blue line) and EC (red line), as measured in the DSR in groundwater monitoring well numbers (a) 301, (b) 336, (c) 361, and (d) 372.

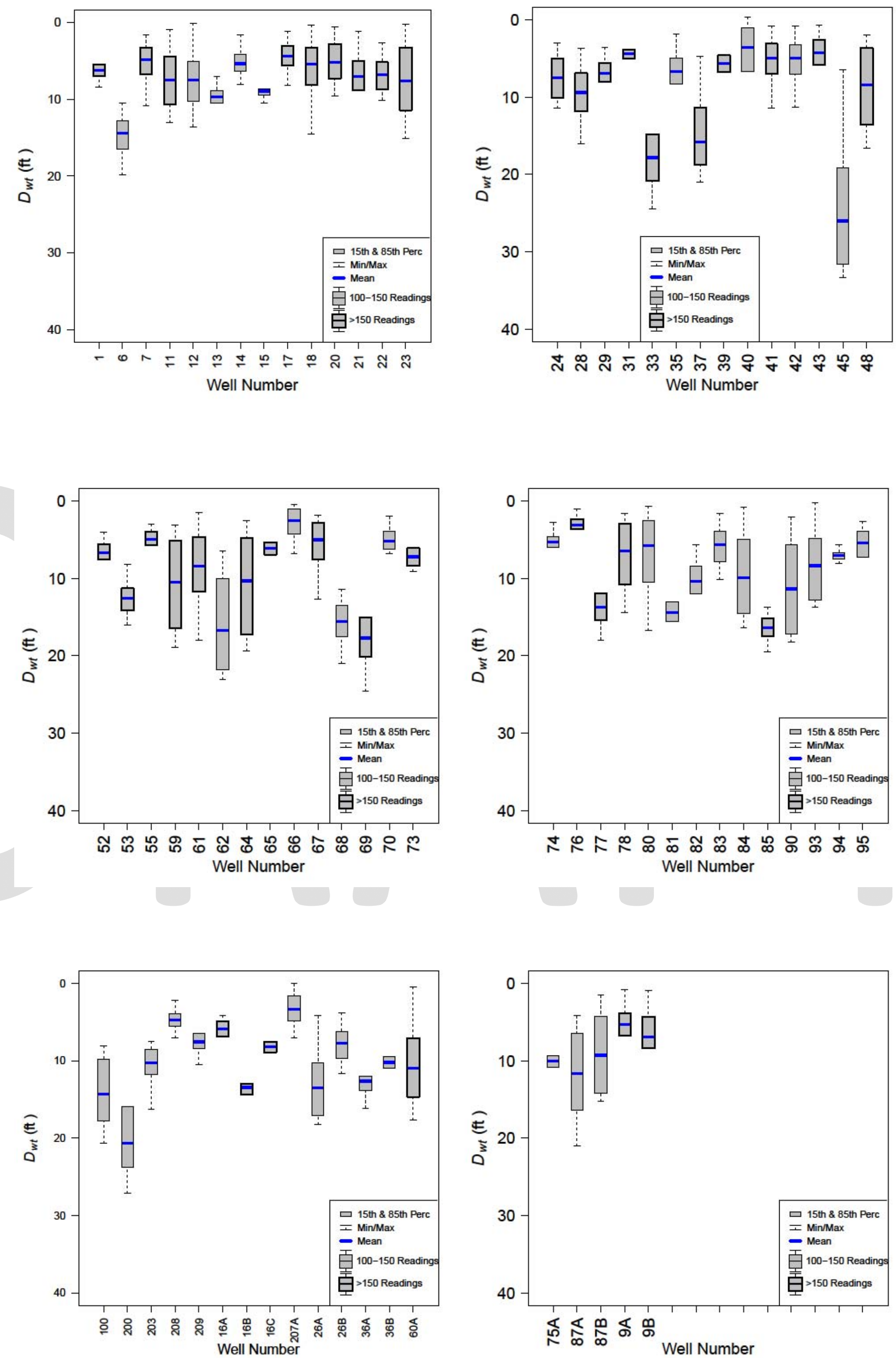


Figure 3.31. Box-and-whisker plots of D_{wt} in groundwater monitoring wells in the USR.

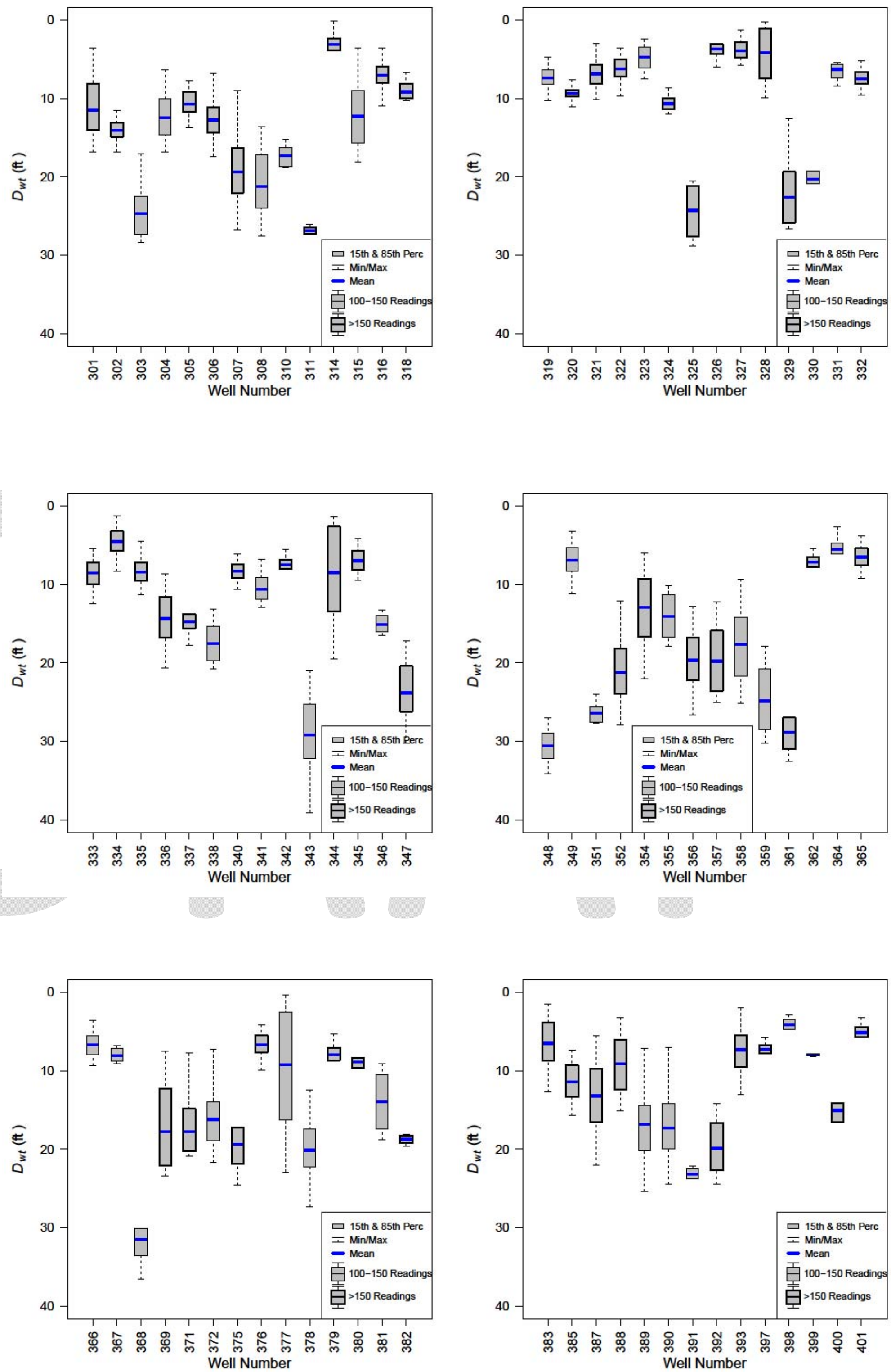


Figure 3.32. Box-and-whisker plots of D_{wt} in groundwater monitoring wells in the DSR.

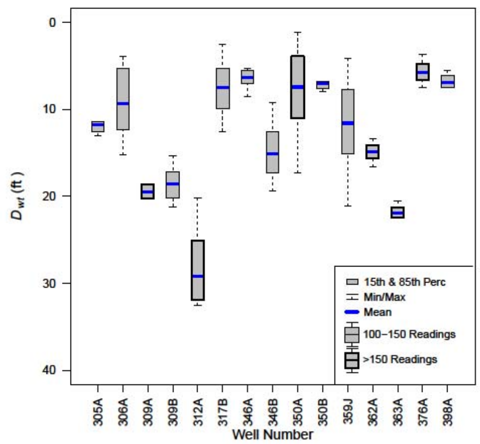


Figure 3.32 (Cont.). Box-and-whisker plots of D_{wt} in groundwater monitoring wells in the DSR.

3.3.4 Groundwater Quality in the LARB Study Regions

3.3.4.1 In-situ Water Quality Parameters in the Groundwater in the LARB Study Regions

Tables A3.19 in Excel File 3F and A3.20 in Excel File 3G on the ARBhwq CD summarize spatial statistics over all sampled groundwater monitoring wells for measured values of EC, *T*, pH, DO, and ORP for each sampling event in the USR and DSR, respectively.

Figure 3.33 shows histograms of all measured values of groundwater EC in the USR and in the DSR over the respective study periods. Temporal variability in EC over the study periods is portrayed in Figures 3.29 and 3.30 for four monitoring wells in the USR and DSR, respectively. Box-and-whisker plots of temporal statistics of EC for all wells within the USR having at least 100 measurements over 1999 – 2012 are shown in Figure 3.34. Similar plots are shown in Figure 3.35 for wells in the DSR over 2002 – 2012. Temporal coefficient of variation, CV_t, in EC over the study periods within monitoring wells ranged from 0.10 to 0.89, averaging 0.28, in the USR and from 0.01 to 0.61, averaging 0.18, in the DSR.

Spatial average values of pH in groundwater monitoring wells ranged from 6.33 to 7.67, with an overall average across the sampling events of 6.97 in the USR. In the DSR, spatial average pH measured in groundwater monitoring wells ranged from 6.20 to 7.47 with an overall average across sampling events of 6.81. Spatial average values of DO in groundwater ranged from 1.51 to 11.15 mg/L, with an overall average across the sampling events of 3.97 mg/L in the USR. Spatial average DO measured in the DSR groundwater ranged from 1.12 to 7.83 mg/L, with an overall average across the sampling events of 3.37 mg/L.

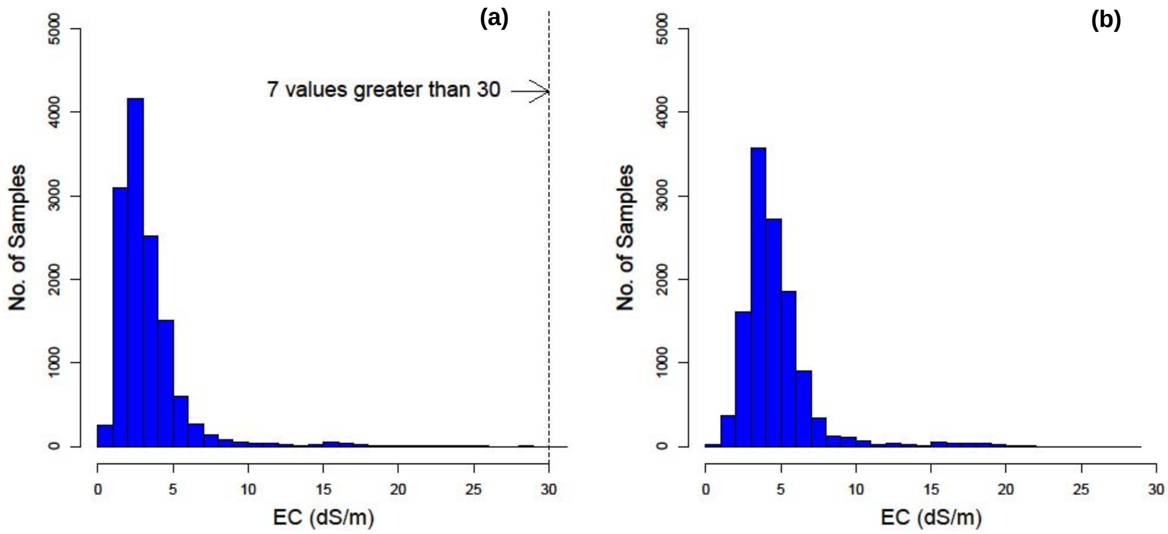


Figure 3.33. Histograms of EC values measured in all routinely-sampled groundwater monitoring wells within the (a) USR and (b) DSR during the study periods.

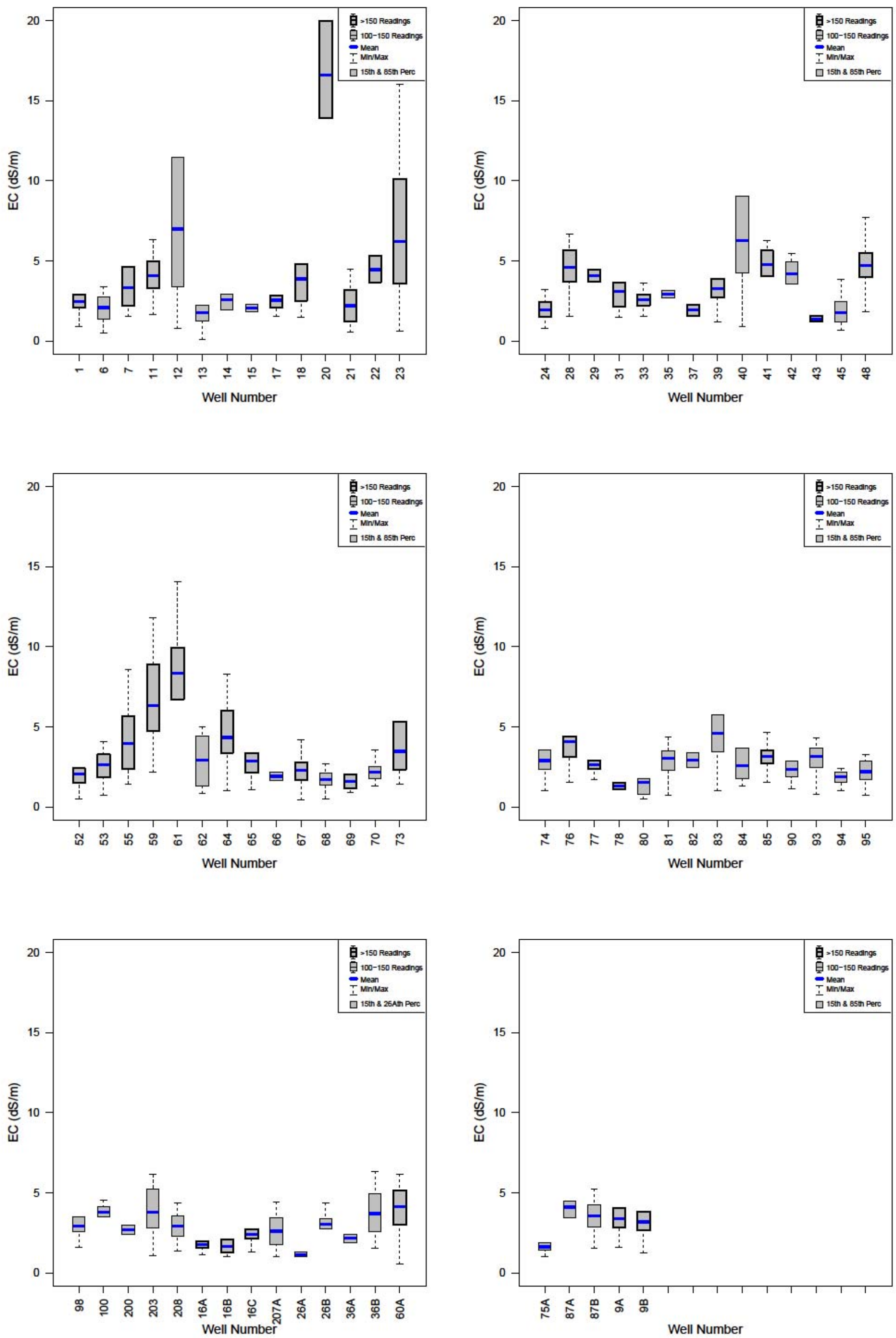


Figure 3.34. Box-and-whisker plots of EC in groundwater monitoring wells in the USR.

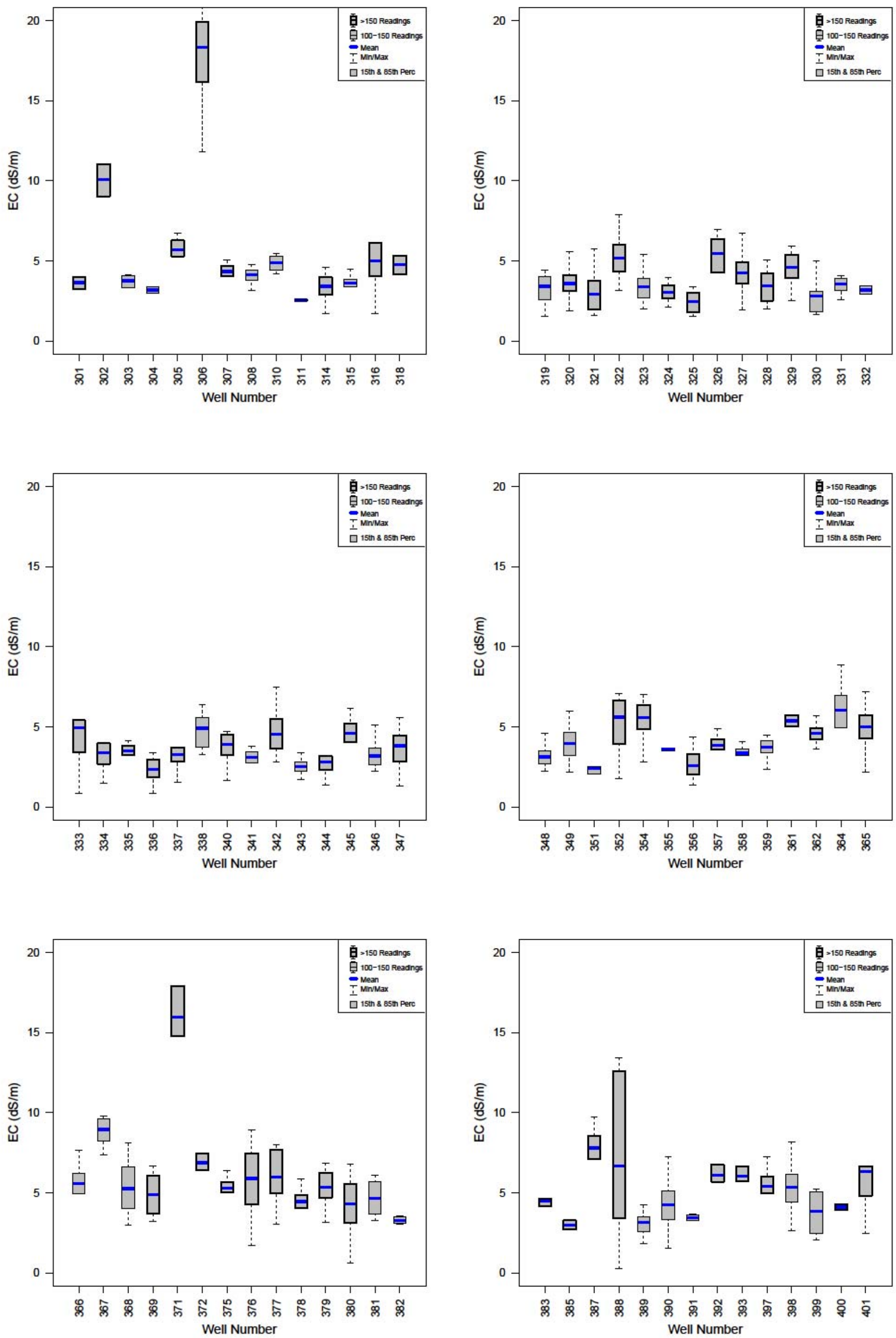


Figure 3.35. Box-and-whisker plots of EC in groundwater monitoring wells in the DSR.

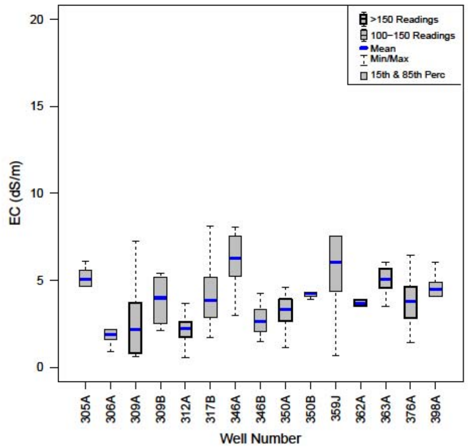


Figure 3.35 (Cont.). Box-and-whisker plots of EC in groundwater monitoring wells in the DSR.

3.3.4.2 Dissolved Chemical Concentrations in Groundwater in the LARB Study Regions

3.3.4.2.1 TDS and Major Salt Ions in Groundwater in the LARB Study Regions

TDS was estimated for each water sample gathered from monitoring wells in the LARB by summing up the concentrations of all major dissolved ions estimated by laboratory analysis of the sample. A summary of the spatial statistics of TDS and the dissolved ions from all monitored groundwater wells are provided in Table A3.21 in Excel File 3H on the ARBhwq CD for all sampling events in the USR and in Table A3.22 in Excel File 3I on the ARBhwq CD for all sampling events in the DSR. Abridged summary statistics for TDS in water samples from monitoring wells in the USR and DSR are given in Table 3.15. Histograms of all measured values of groundwater TDS in the USR and DSR over their study periods are shown in Figure 3.36. Figures 3.37 and 3.38 show box-and-whisker plots of the temporal statistics of TDS for all wells having at least 100 measurements over 1999 – 2011 for the USR and over 2002 – 2011 for the DSR, respectively. Values of TDS in individual monitoring wells displayed moderate temporal variability, with temporal coefficient of variation, CV_t, in TDS over the study periods within monitoring wells ranging from 0.05 to 1.19, averaging 0.24, in the USR and from 0.06 to 1.01, averaging 0.19, in the DSR.

Table 3.15. Abridged statistical summary of TDS in water samples gathered from groundwater monitoring wells within the USR and DSR.

USR						
Sampling Trip Description (Water Quality)				TDS (mg/L)		
Trip Number	Start Date	End Date	No. Wells Visited	No. Evalu-ations	Average	CV
158 (S1)	6/17/2006	6/20/2006	-	40	3156	0.87
170 (S2)	5/21/2007	5/24/2007	-	41	4135	1.65
175 (S3)	10/6/2007	10/7/2007	52	35	3596	1.43
178 (S4)	3/17/2008	3/22/2008	52	30	3960	1.28
181 (S5)	6/21/2008	6/25/2008	-	74	2809	0.79
184 (S6)	8/14/2008	8/15/2008	57	39	3015	0.95
185 (S7)	1/15/2009	1/16/2009	51	30	3350	0.64
186 (S8)	2/5/2009	2/5/2009	14	8	1679	0.44
187 (S9)	5/13/2009	5/14/2009	52	34	3644	1.31
190 (S10)	7/21/2009	7/23/2009	51	32	2956	0.93
193 (S11)	11/19/2009	11/20/2009	51	31	3322	0.94
195 (S12)	3/12/2010	3/18/2010	-	24	3691	0.81
196 (S13)	5/14/2010	5/16/2010	39	29	3484	0.88
200 (S14)	7/20/2010	7/21/2010	50	35	2942	0.56
201 (S15)	8/10/2010	8/13/2010	-	27	2652	0.45
205 (S16)	5/20/2011	5/21/2011	36	19	3485	1.02

DSR						
Sampling Trip Description (Water Quality)				TDS (mg/L)		
Trip Number	Start Date	End Date	No. Wells Visited	No. Evalu-ations	Average	CV
27 (S1)	4/25/2003	5/4/2003	50	0		
29 (S2)	5/29/2003	5/30/2003	-	17	3537	0.26
30 (S3)	6/3/2003	6/6/2003	-	8	3643	0.22
31 (S4)	6/10/2003	6/13/2003	-	19	5600	0.78
33 (S5)	6/30/2003	7/3/2003	-	0		
34 (S6)	7/7/2003	7/8/2003	-	0		
38 (S7)	7/27/2003	7/31/2003	-	42	4505	0.71
45 (S8)	10/25/2003	11/2/2003	50	0		
47 (S9)	1/12/2004	1/17/2004	-	47	3814	0.57
49 (S10)	3/15/2004	3/19/2004	-	0		
51 (S11)	4/30/2004	5/6/2004	-	45	4870	0.62
54 (S12)	6/1/2004	6/4/2004	54	0		
58 (S13)	6/28/2004	7/1/2004	-	48	4743	0.89
62 (S14)	8/2/2004	8/6/2004	-	0		
68 (S15)	11/4/2004	11/8/2004	54	50	4080	0.56
71 (S16)	1/10/2005	1/17/2005	-	0		
73 (S17)	3/15/2005	3/20/2005	-	48	4180	0.49
80 (S18)	6/27/2005	7/2/2005	-	0		
83 (S19)	7/19/2005	7/23/2005	-	49	3841	0.52
86 (S20)	8/11/2005	8/19/2005	-	0		
89 (S21)	11/18/2005	11/22/2005	-	45	4132	0.53
91 (S22)	1/10/2006	1/13/2006	59	0		
94 (S23)	3/11/2006	3/15/2006	-	43	3947	0.57

Table 3.15 (Cont.)

DSR						
Sampling Trip Description (Water Quality)				TDS (mg/L)		
Trip Number	Start Date	End Date	No. Wells Visited	No. Evalu-ations	Average	CV
96 (S24)	5/13/2006	5/16/2006	60	0		
100 (S25)	6/12/2006	6/15/2006	-	45	4113	0.58
104 (S26)	7/11/2006	7/13/2006	-	0		
107 (S27)	8/7/2006	8/10/2006	-	45	4106	0.58
110 (S28)	11/18/2006	11/20/2006	61	0		
113 (S29)	3/10/2007	3/11/2007	61	37	4934	1.16
116 (S30)	5/15/2007	5/18/2007	-	0		
119 (S31)	6/19/2007	6/22/2007	-	48	4331	0.73
124 (S32)	7/22/2007	7/24/2007	-	0		
126 (S33)	8/13/2007	8/15/2007	-	45	3928	0.47
129 (S34)	11/17/2007	11/19/2007	60	47	4056	0.67
132 (S35)	1/15/2008	1/17/2008	61	0		
136 (S36)	5/20/2008	5/21/2008	59	39	4065	0.66
142 (S37)	7/12/2008	7/16/2008	46	34	3389	0.37
146 (S38)	11/20/2008	11/20/2008	61	41	4263	0.67
149 (S39)	3/13/2009	3/14/2009	61	36	4114	0.62
152 (S40)	6/24/2009	6/25/2009	61	37	4384	0.63
156 (S41)	8/27/2009	8/29/2009	60	34	4075	0.38
158 (S42)	1/3/2010	1/7/2010	-	28	3219	0.46
159 (S43)	3/13/2010	3/16/2010	-	28	3821	0.42
161 (S44)	6/8/2010	6/9/2010	48	28	4360	0.35
164 (S45)	8/10/2010	8/11/2010	-	23	3983	0.52
168 (S46)	5/18/2011	5/19/2011	48	28	3990	0.37

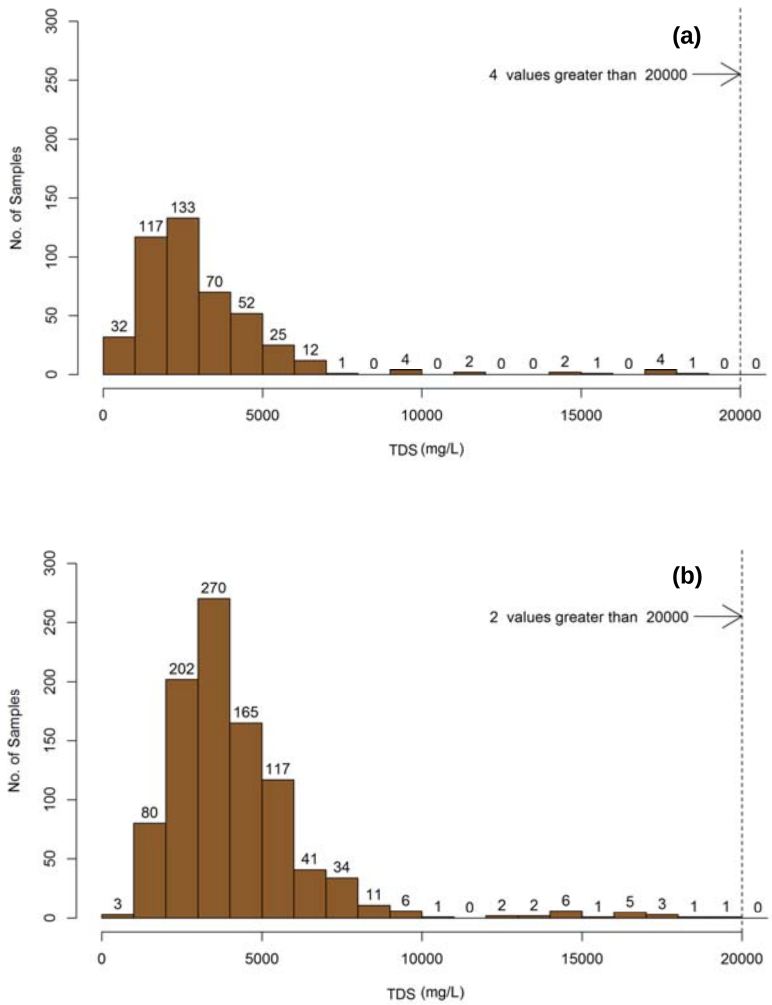


Figure 3.36. Histograms of TDS values measured in all routinely-sampled groundwater monitoring wells within the (a) USR and (b) DSR during the study periods.

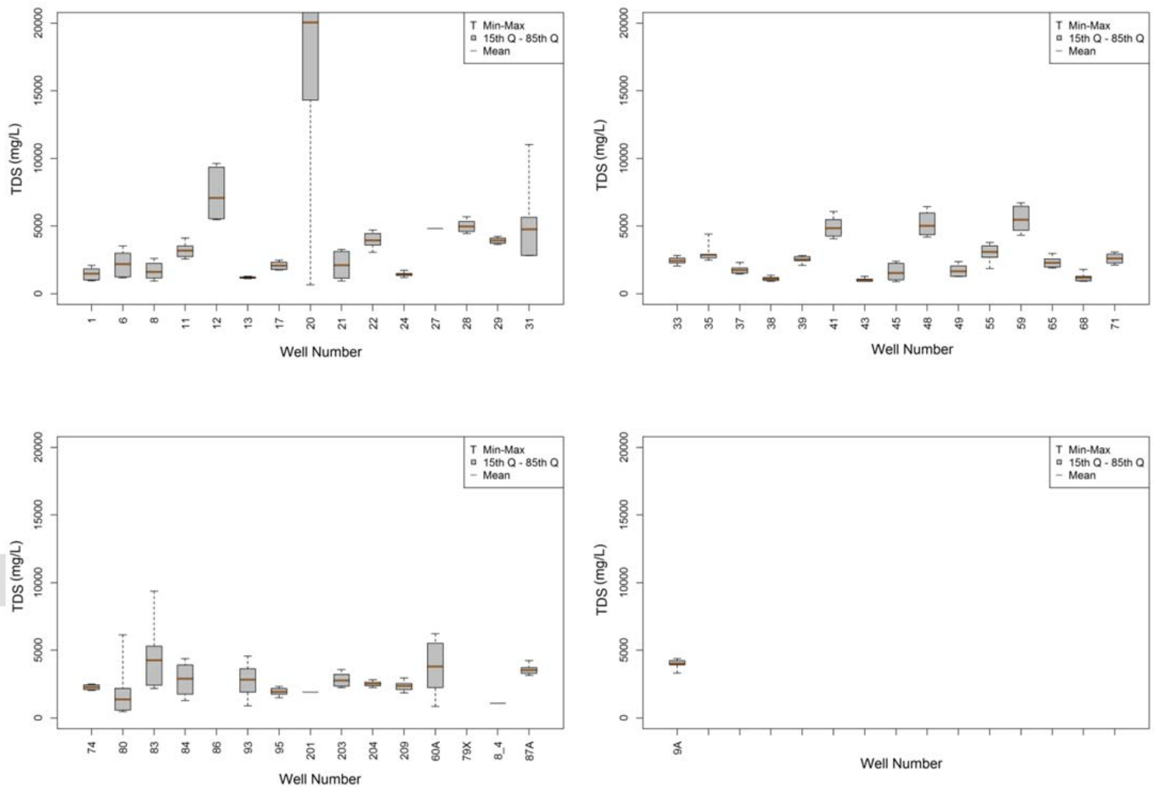


Figure 3.37. Box-and-whisker plots of TDS in water samples from groundwater monitoring wells in the USR.

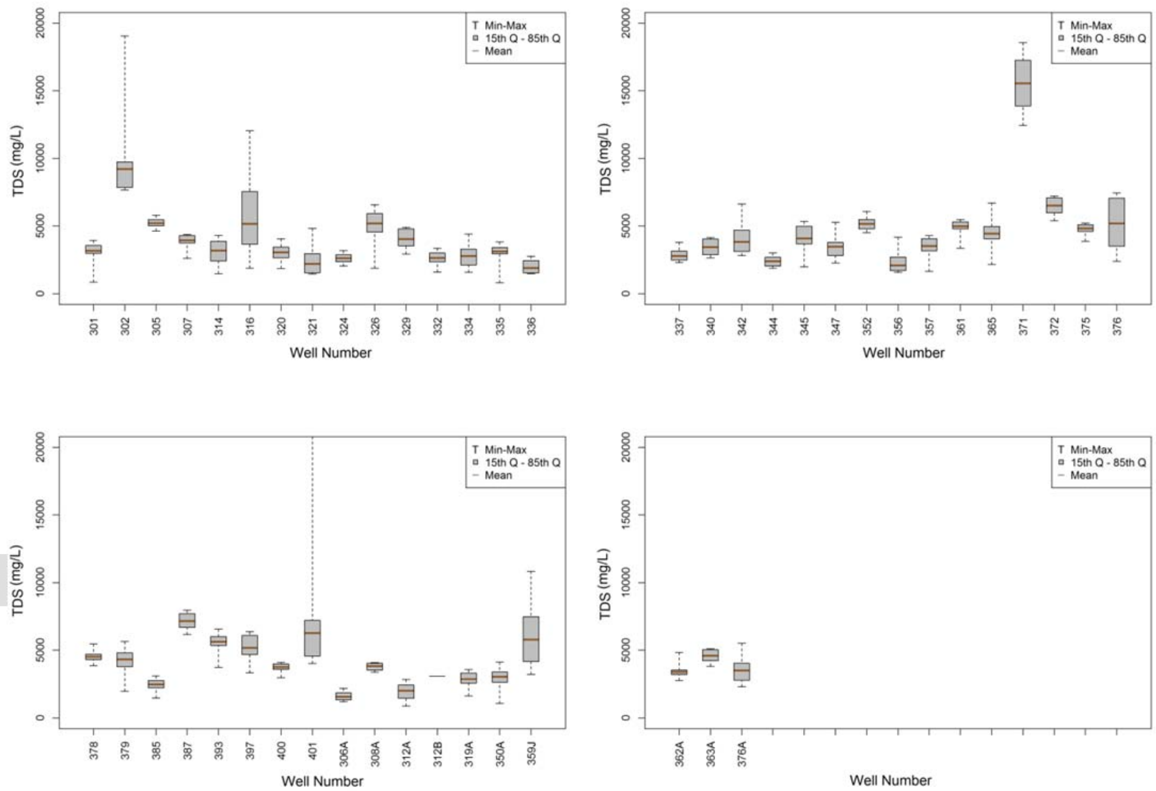


Figure 3.38. Box-and-whisker plots of TDS in water samples from groundwater monitoring wells in the DSR.

Tables 3.16 and 3.17 provide abridged statistical summaries of the principal cations in water samples from groundwater monitoring wells in the USR and DSR, respectively. Similar summaries are provided in Tables 3.18 and 3.19 for the principal anions in groundwater samples in the USR and DSR, respectively. The overall spatiotemporal distribution of the principal cations and anions estimated from groundwater monitoring well samples are portrayed in the histograms in Figure 3.39 and 3.40, respectively, for the USR and in Figures 3.41 and 3.42, respectively, for the DSR.

Table 3.16. Abridged statistical summary of principal cation concentrations in groundwater samples from monitoring wells in the USR.

Sampling Trip Description (Water Quality)				C_{Ca} (mg/L)			C_{Na} (mg/L)			C_{Mg} (mg/L)		
Trip Number	Start Date	End Date	No. Wells Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
158 (S1)	6/17/2006	6/20/2006	-	39	345.2	0.37	40	408.3	1.59	40	172.9	0.87
170 (S2)	5/21/2007	5/24/2007	-	41	389.2	0.38	41	555.5	2.29	41	264.9	2.84
175 (S3)	10/6/2007	10/7/2007	52	35	330.5	0.43	35	477.4	2.22	35	204.7	1.94
178 (S4)	3/17/2008	3/22/2008	52	30	360.2	0.38	30	465.8	1.93	30	248.1	1.72
181 (S5)	6/21/2008	6/25/2008	-	74	334.0	0.40	74	314.1	1.45	74	153.2	1.08
184 (S6)	8/14/2008	8/15/2008	57	39	355.7	0.43	39	361.5	1.67	39	169.2	1.31
185 (S7)	1/15/2009	1/16/2009	51	30	398.2	0.35	30	394.1	1.14	30	153.7	0.80
186 (S8)	2/5/2009	2/5/2009	14	8	278.4	0.44	8	122.0	0.45	8	71.9	0.49
187 (S9)	5/13/2009	5/14/2009	52	34	341.8	0.40	34	430.2	2.17	34	219.7	1.91
190 (S10)	7/21/2009	7/23/2009	51	32	322.5	0.41	32	338.6	1.56	32	163.6	1.26
193 (S11)	11/19/2009	11/20/2009	51	31	345.7	0.40	31	390.9	1.70	31	203.7	1.37
195 (S12)	3/12/2010	3/18/2010	-	24	385.4	0.41	24	423.0	1.28	24	208.8	1.09
196 (S13)	5/14/2010	5/16/2010	39	29	365.2	0.37	29	407.7	1.51	29	193.9	1.08
200 (S14)	7/20/2010	7/21/2010	50	35	363.3	0.42	35	283.9	0.79	35	156.7	0.78
201 (S15)	8/10/2010	8/13/2010	-	27	349.0	0.43	27	262.1	0.65	27	133.7	0.65
205 (S16)	5/20/2011	5/21/2011	36	19	360.0	0.37	19	428.4	1.74	19	185.0	1.23

Table 3.17. Abridged statistical summary of principal cation concentrations in groundwater samples from monitoring wells in the DSR.

Sampling Trip Description (Water Quality)				C_{Ca} (mg/L)			C_{Na} (mg/L)			C_{Mg} (mg/L)		
Trip Number	Start Date	End Date	No. Wells Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
27 (S1)	4/25/2003	5/4/2003	50	0			0			0		
29 (S2)	5/29/2003	5/30/2003	-	17	409.1	0.22	17	438.6	0.33	17	175.1	0.21
30 (S3)	6/3/2003	6/6/2003	-	8	383.8	0.13	8	496.4	0.29	8	155.5	0.28
31 (S4)	6/10/2003	6/13/2003	-	19	390.7	0.29	19	923.6	1.02	19	299.5	1.03
33 (S5)	6/30/2003	7/3/2003	-	0			0			0		
34 (S6)	7/7/2003	7/8/2003	-	0			0			0		
38 (S7)	7/27/2003	7/31/2003	-	42	397.4	0.24	42	610.8	1.06	42	236.3	0.93
45 (S8)	10/25/2003	11/2/2003	50	0			0			0		
47 (S9)	1/12/2004	1/17/2004	-	47	380.9	0.22	47	572.6	0.94	47	165.9	0.83
49 (S10)	3/15/2004	3/19/2004	-	0			0			0		
51 (S11)	4/30/2004	5/6/2004	-	45	403.9	0.25	45	701.7	0.86	45	229.8	0.77
54 (S12)	6/1/2004	6/4/2004	54	0			0			0		
58 (S13)	6/28/2004	7/1/2004	-	48	369.7	0.34	48	782.9	1.42	48	227.5	1.01
62 (S14)	8/2/2004	8/6/2004	-	0			0			0		
68 (S15)	11/4/2004	11/8/2004	54	50	391.8	0.31	50	635.3	0.83	50	201.7	0.73
71 (S16)	1/10/2005	1/17/2005	-	0			0			0		
73 (S17)	3/15/2005	3/20/2005	-	48	349.8	0.28	48	630.4	0.72	48	209.2	0.66
80 (S18)	6/27/2005	7/2/2005	-	0			0			0		
83 (S19)	7/19/2005	7/23/2005	-	49	380.4	0.27	49	600.0	0.80	49	162.2	0.73
86 (S20)	8/11/2005	8/19/2005	-	0			0			0		
89 (S21)	11/18/2005	11/22/2005	-	45	397.9	0.27	45	585.7	0.82	45	200.4	0.72
91 (S22)	1/10/2006	1/13/2006	59	0			0			0		
94 (S23)	3/11/2006	3/15/2006	-	43	373.3	0.30	43	617.2	0.85	43	195.2	0.73
96 (S24)	5/13/2006	5/16/2006	60	0			0			0		
100 (S25)	6/12/2006	6/15/2006	-	45	366.3	0.32	45	664.0	0.88	45	214.6	0.70
104 (S26)	7/11/2006	7/13/2006	-	0			0			0		
107 (S27)	8/7/2006	8/10/2006	-	45	365.6	0.34	45	617.9	0.86	45	214.3	0.60

Table 3.17 (Cont.)

Sampling Trip Description (Water Quality)				C_{Ca} (mg/L)			C_{Na} (mg/L)			C_{Mg} (mg/L)		
Trip Number	Start Date	End Date	No. Wells Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
110 (S28)	11/18/2006	11/20/2006	61	0			0			0		
113 (S29)	3/10/2007	3/11/2007	61	37	371.4	0.33	37	830.4	1.70	37	245.8	1.50
116 (S30)	5/15/2007	5/18/2007	-	0			0			0		
119 (S31)	6/19/2007	6/22/2007	-	48	395.4	0.29	48	657.6	1.08	48	200.4	0.93
124 (S32)	7/22/2007	7/24/2007	-	0			0			0		
126 (S33)	8/13/2007	8/15/2007	-	45	378.7	0.33	45	565.6	0.71	45	178.7	0.57
129 (S34)	11/17/2007	11/19/2007	60	47	373.8	0.33	47	591.3	1.01	47	235.6	0.84
132 (S35)	1/15/2008	1/17/2008	61	0			0			0		
136 (S36)	5/20/2008	5/21/2008	59	39	379.4	0.29	39	650.8	0.98	39	231.9	0.79
142 (S37)	7/12/2008	7/16/2008	46	34	378.4	0.29	34	446.6	0.57	34	170.1	0.45
146 (S38)	11/20/2008	11/20/2008	61	41	394.3	0.33	41	672.5	0.95	41	180.3	1.01
149 (S39)	3/13/2009	3/14/2009	61	36	390.1	0.30	36	590.8	1.00	36	186.4	0.89
152 (S40)	6/24/2009	6/25/2009	61	37	377.7	0.29	37	664.9	1.03	37	245.8	0.86
156 (S41)	8/27/2009	8/29/2009	60	34	383.8	0.29	34	558.9	0.56	34	205.4	0.42
158 (S42)	1/3/2010	1/7/2010	-	28	335.6	0.39	28	446.8	0.63	28	163.9	0.49
159 (S43)	3/13/2010	3/16/2010	-	28	378.0	0.35	28	519.6	0.60	28	195.1	0.48
161 (S44)	6/8/2010	6/9/2010	48	28	420.0	0.24	28	588.2	0.56	28	217.3	0.46
164 (S45)	8/10/2010	8/11/2010	-	23	410.4	0.29	23	572.3	0.94	23	205.9	0.61
168 (S46)	5/18/2011	5/19/2011	48	28	386.6	0.21	28	532.8	0.57	28	214.5	0.46

Table 3.18. Abridged statistical summary of principal anion concentrations in groundwater samples from monitoring wells in the USR.

Sampling Trip Description (Water Quality)				C_{SO_4-S} (mg/L)			C_{HCO_3} (mg/L)			C_{Cl} (mg/L)		
Trip Number	Start Date	End Date	No. Wells Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
158 (S1)	6/17/2006	6/20/2006	-	38	604.8	0.98	40	410.1	0.28	40	75.9	1.37
170 (S2)	5/21/2007	5/24/2007	-	41	789.0	1.91	41	410.7	0.51	41	116.7	1.72
175 (S3)	10/6/2007	10/7/2007	52	35	671.0	1.65	35	427.8	0.51	35	110.7	1.46
178 (S4)	3/17/2008	3/22/2008	52	30	780.0	1.45	30	413.7	0.49	30	107.4	1.62
181 (S5)	6/21/2008	6/25/2008	-	74	510.5	0.88	74	364.1	0.36	74	96.6	2.17
184 (S6)	8/14/2008	8/15/2008	57	39	547.6	1.11	39	389.5	0.45	39	79.4	1.09
185 (S7)	1/15/2009	1/16/2009	51	30	623.0	0.76	30	421.5	0.44	30	94.1	0.77
186 (S8)	2/5/2009	2/5/2009	14	8	265.4	0.54	8	355.3	0.32	8	43.1	0.34
187 (S9)	5/13/2009	5/14/2009	52	34	685.9	1.51	34	469.9	0.70	34	107.1	1.53
190 (S10)	7/21/2009	7/23/2009	51	32	548.2	1.10	32	381.5	0.46	32	79.6	1.19
193 (S11)	11/19/2009	11/20/2009	51	31	589.8	1.09	31	494.1	0.81	31	98.6	1.31
195 (S12)	3/12/2010	3/18/2010	-	24	705.9	0.93	24	430.3	0.33	24	93.5	0.94
196 (S13)	5/14/2010	5/16/2010	39	29	671.2	1.02	29	394.2	0.34	29	84.5	1.40
200 (S14)	7/20/2010	7/21/2010	50	35	562.8	0.67	35	361.8	0.29	35	70.1	1.08
201 (S15)	8/10/2010	8/13/2010	-	27	476.2	0.56	27	386.9	0.29	27	66.8	0.61
205 (S16)	5/20/2011	5/21/2011	36	19	668.7	1.16	19	359.0	0.30	19	111.3	1.33

Table 3.19. Abridged statistical summary of principal anion concentrations in groundwater samples from monitoring wells in the DSR.

Sampling Trip Description (Water Quality)				C_{SO_4-S} (mg/L)			C_{HCO_3} (mg/L)			C_{Cl} (mg/L)		
Trip Number	Start Date	End Date	No. Wells Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
27 (S1)	4/25/2003	5/4/2003	50	0			0			0		
29 (S2)	5/29/2003	5/30/2003	-	17	679.6	0.33	17	335.0	0.23	17	131.0	1.10
30 (S3)	6/3/2003	6/6/2003	-	8	705.3	0.24	8	377.3	0.14	8	101.5	0.46
31 (S4)	6/10/2003	6/13/2003	-	19	1033.4	0.78	19	421.0	0.37	19	446.1	2.34
33 (S5)	6/30/2003	7/3/2003	-	0			0			0		
34 (S6)	7/7/2003	7/8/2003	-	0			0			0		
38 (S7)	7/27/2003	7/31/2003	-	42	850.7	0.64	42	372.1	0.28	42	256.2	2.66
45 (S8)	10/25/2003	11/2/2003	50	0			0			0		
47 (S9)	1/12/2004	1/17/2004	-	47	697.8	0.59	47	382.4	0.35	47	121.5	0.50
49 (S10)	3/15/2004	3/19/2004	-	0			0			0		
51 (S11)	4/30/2004	5/6/2004	-	45	942.0	0.57	45	379.1	0.37	45	240.1	1.84
54 (S12)	6/1/2004	6/4/2004	54	0			0			0		
58 (S13)	6/28/2004	7/1/2004	-	48	841.9	0.65	48	368.7	0.33	48	385.4	3.24
62 (S14)	8/2/2004	8/6/2004	-	0			0			0		
68 (S15)	11/4/2004	11/8/2004	54	50	757.7	0.56	50	354.7	0.39	50	195.1	1.13
71 (S16)	1/10/2005	1/17/2005	-	0			0			0		
73 (S17)	3/15/2005	3/20/2005	-	48	802.7	0.55	48	405.9	0.35	48	149.5	0.79
80 (S18)	6/27/2005	7/2/2005	-	0			0			0		
83 (S19)	7/19/2005	7/23/2005	-	49	698.6	0.54	49	382.8	0.36	49	184.0	1.13
86 (S20)	8/11/2005	8/19/2005	-	0			0			0		
89 (S21)	11/18/2005	11/22/2005	-	45	781.2	0.56	45	399.9	0.29	45	175.8	0.72
91 (S22)	1/10/2006	1/13/2006	59	0			0			0		
94 (S23)	3/11/2006	3/15/2006	-	43	742.6	0.60	43	355.6	0.36	43	148.9	0.87
96 (S24)	5/13/2006	5/16/2006	60	0			0			0		
100 (S25)	6/12/2006	6/15/2006	-	45	749.0	0.62	45	432.5	0.39	45	159.2	1.19

Table 3.19 (Cont.)

Sampling Trip Description (Water Quality)				C_{SO_4-S} (mg/L)			C_{HCO_3} (mg/L)			C_{Cl} (mg/L)		
Trip Number	Start Date	End Date	No. Wells Visited	No. Tests	Average	CV	No. Tests	Average	CV	No. Tests	Average	CV
104 (S26)	7/11/2006	7/13/2006	-	0			0			0		
107 (S27)	8/7/2006	8/10/2006	-	45	766.8	0.61	45	401.1	0.39	45	176.0	1.15
110 (S28)	11/18/2006	11/20/2006	61	0			0			0		
113 (S29)	3/10/2007	3/11/2007	61	37	833.6	0.79	37	403.8	0.35	37	536.8	3.91
116 (S30)	5/15/2007	5/18/2007	-	0			0			0		
119 (S31)	6/19/2007	6/22/2007	-	48	795.0	0.77	48	425.5	0.41	48	233.3	1.33
124 (S32)	7/22/2007	7/24/2007	-	0			0			0		
126 (S33)	8/13/2007	8/15/2007	-	45	726.6	0.47	45	397.3	0.27	45	200.1	1.06
129 (S34)	11/17/2007	11/19/2007	60	47	748.4	0.73	47	402.8	0.33	47	180.4	1.05
132 (S35)	1/15/2008	1/17/2008	61	0			0			0		
136 (S36)	5/20/2008	5/21/2008	59	39	728.0	0.69	39	382.6	0.25	39	207.5	1.16
142 (S37)	7/12/2008	7/16/2008	46	34	603.9	0.42	34	422.1	0.38	34	134.6	0.67
146 (S38)	11/20/2008	11/20/2008	61	41	771.4	0.71	41	427.7	0.47	41	242.9	1.17
149 (S39)	3/13/2009	3/14/2009	61	36	769.1	0.66	36	399.8	0.25	36	204.2	1.01
152 (S40)	6/24/2009	6/25/2009	61	37	819.1	0.61	37	394.0	0.29	37	211.7	1.11
156 (S41)	8/27/2009	8/29/2009	60	34	772.5	0.38	34	401.3	0.26	34	173.3	0.99
158 (S42)	1/3/2010	1/7/2010	-	28	586.5	0.47	28	344.8	0.24	28	141.7	0.92
159 (S43)	3/13/2010	3/16/2010	-	28	729.5	0.43	28	350.0	0.26	28	155.4	0.89
161 (S44)	6/8/2010	6/9/2010	48	28	824.3	0.36	28	415.7	0.43	28	208.6	0.87
164 (S45)	8/10/2010	8/11/2010	-	23	728.8	0.51	23	401.5	0.26	23	178.4	1.06
168 (S46)	5/18/2011	5/19/2011	48	28	750.0	0.40	28	400.0	0.32	28	176.4	0.66

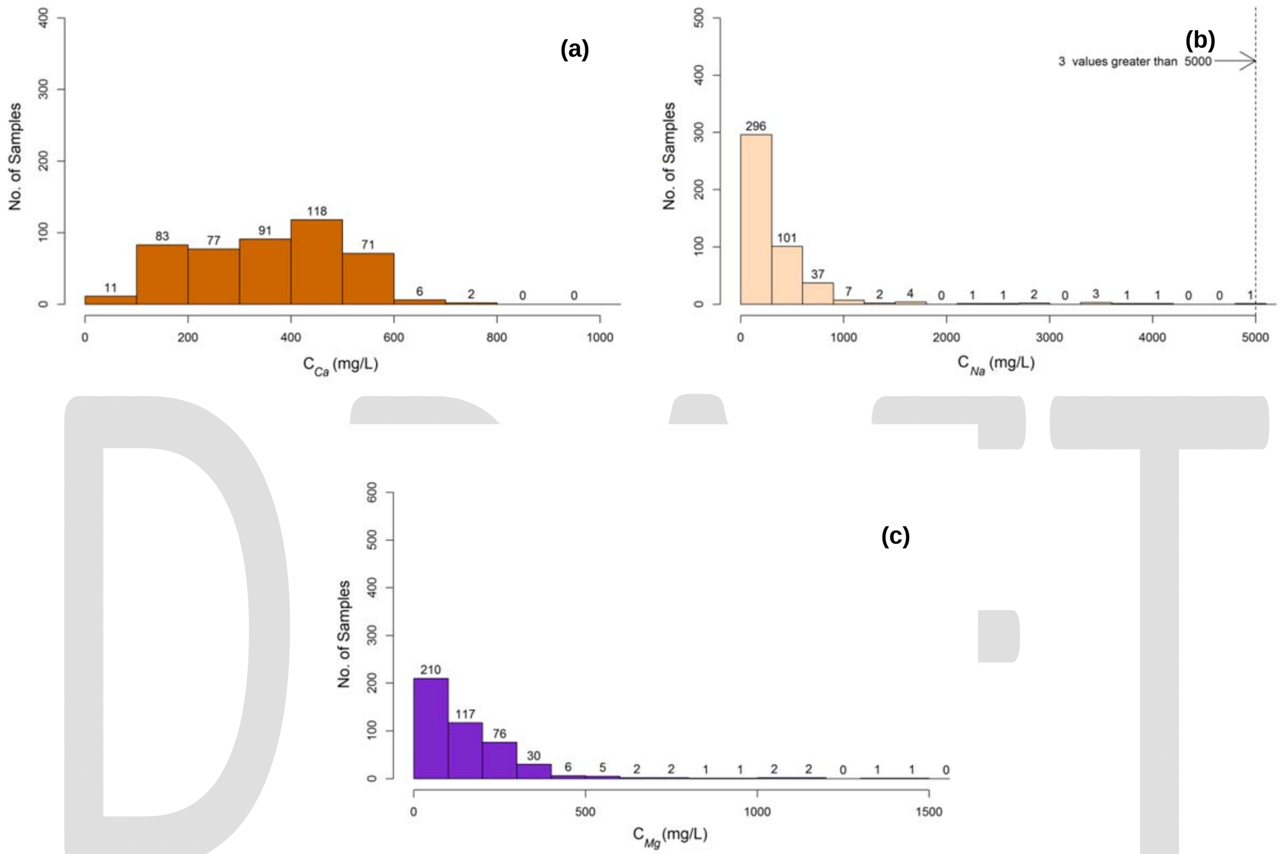


Figure 3.39. Frequency histograms of all values of (a) C_{Ca}, (b) C_{Na}, and (c) C_{Mg} in water samples from groundwater monitoring wells in the USR.

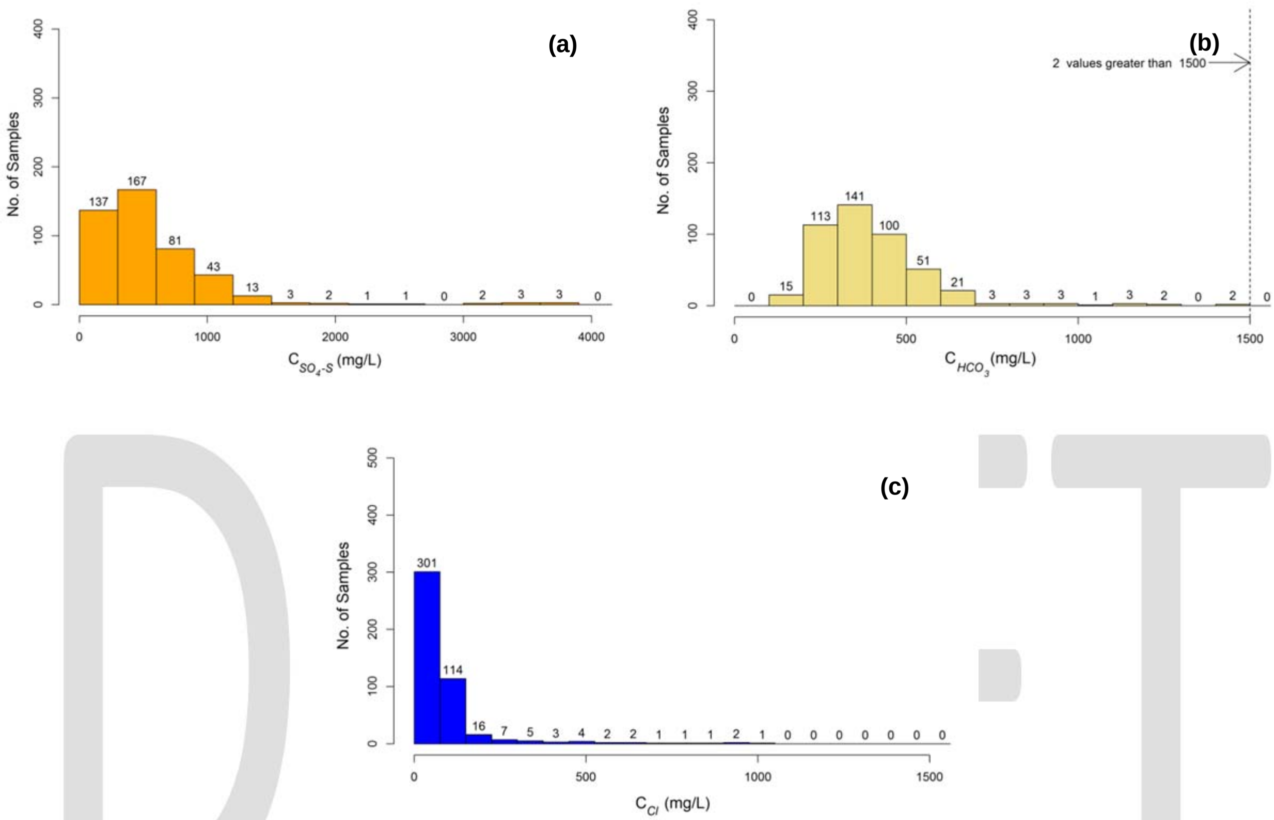


Figure 3.40. Frequency histograms of all values (a) C_{SO_4-S}, (b) C_{HCO_3}, and (c) C_{Cl} in water samples from groundwater monitoring wells in the USR.

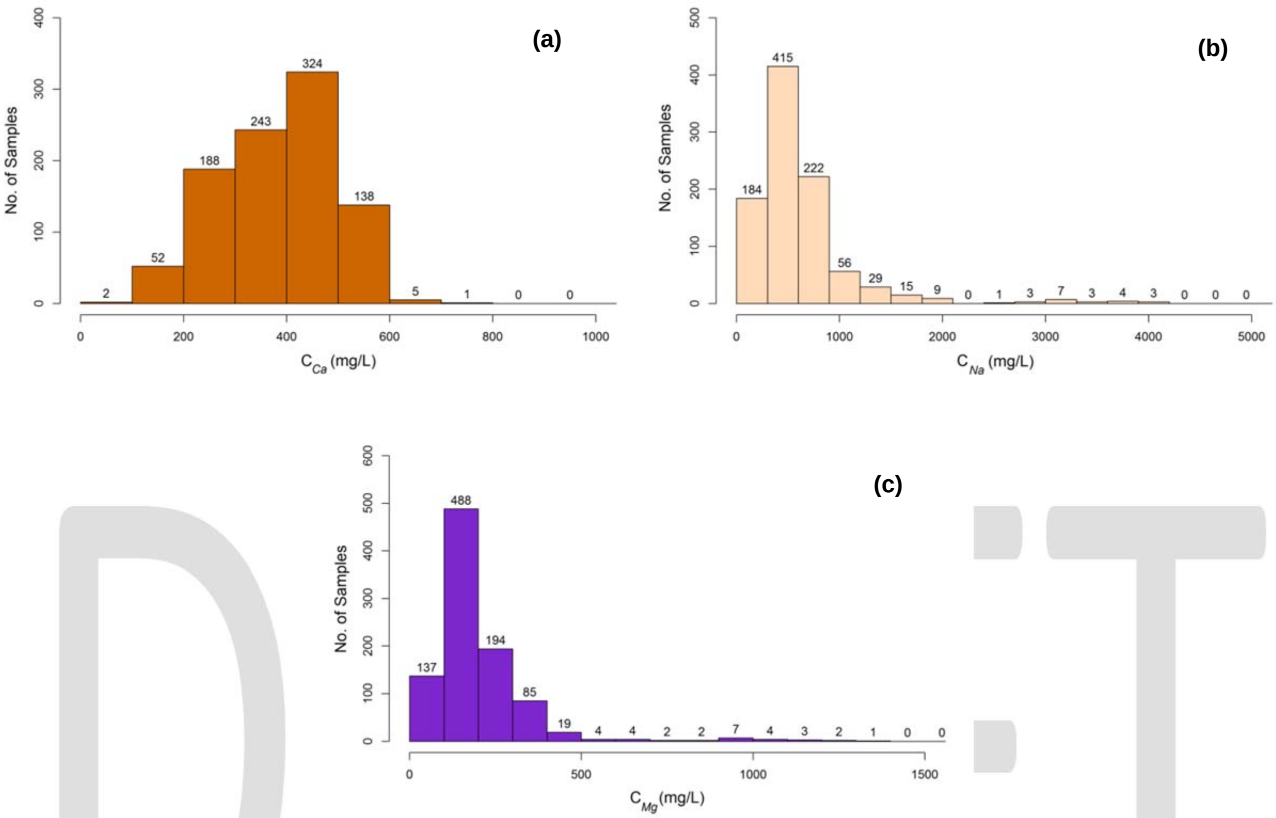


Figure 3.41. Frequency histograms of all values of (a) C_{Ca}, (b) C_{Na}, and (c) C_{Mg} in water samples from groundwater monitoring wells in the DSR.

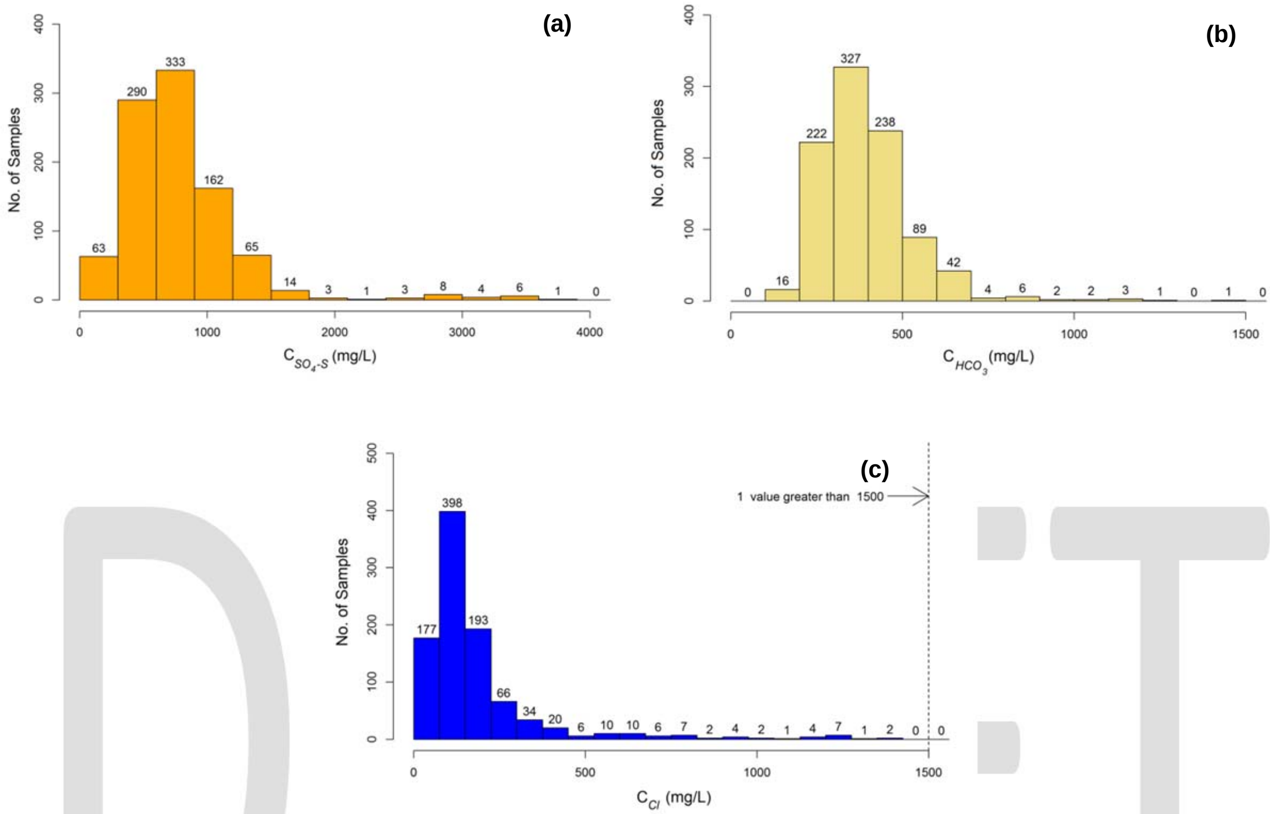


Figure 3.42. Frequency histograms of all values (a) C_{SO_4-S}, (b) C_{HCO_3}, and (c) C_{Cl} in water samples from groundwater monitoring wells in the DSR.

For principal cations in all groundwater samples from the USR, the average milliequivalent fraction of TDS is 23% for Ca, 14% for Na, and 14% for Mg. In the DSR, the relative fractions are 17% for Ca, 20% for Na, and 13% for Mg. For principal anions in the surface water samples from the USR the average fractions are 37% for SO_4, 10% for HCO_3, and 3% for Cl. In the DSR, the principal anion fractions are 39% for SO_4, 6% for HCO_3, and 4% for Cl. Thus, similar to the surface water samples, groundwater samples reveal Ca/Na- SO_4 type waters with the sodium cation growing in prominence in the downstream direction, perhaps indicative of cation exchange and an exceedance of gypsum solubility.

3.3.4.2.2 Nitrate in Groundwater in the LARB

Histograms of C_{NO_3-N} in samples from groundwater monitoring wells in the USR and DSR during the study periods are shown in Figure 3.43 along with the chronic drinking water standard (85th percentile) of 10 mg/L. The 85th percentile value of C_{NO_3-N} measured in groundwater in the USR is 7.7 mg/L and in the DSR is 6.4 mg/L.

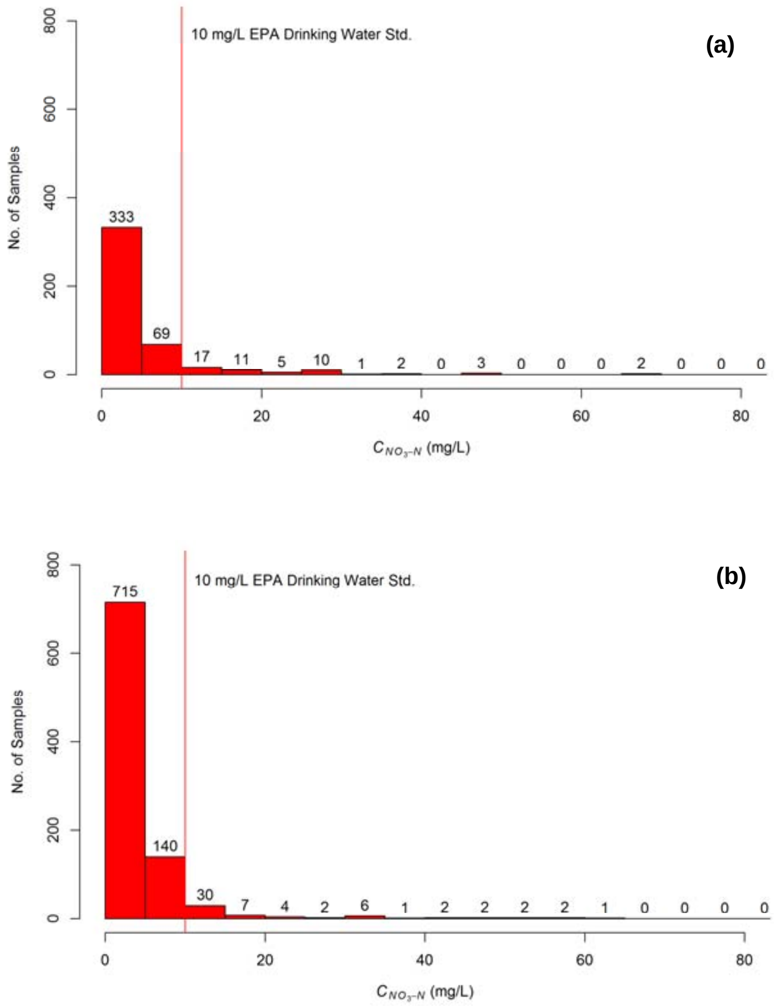


Figure 3.43. Histograms of all C_{NO_3-N} values measured in all routinely-sampled groundwater monitoring wells within the (a) USR and (b) DSR during the study periods. The red vertical line depicts the drinking water standard of 10 mg/L (85th percentile value).

3.3.4.2.3 Dissolved Selenium and Uranium in Groundwater in the LARB

Dissolved Se in the alluvial aquifer of the LARB is derived from Se that is imported from upstream by way of the irrigation water that recharges the water table (from excess irrigation and canal seepage) and from oxidation of selenide in bedrock shale, shale outcrops, and shale residuum (Gates et al. 2009, Bailey et al. 2012). Groundwater return flow to the Arkansas River and its tributaries serves to load the stream network, contributing to the in-stream concentrations that substantially exceed the State and Federal chronic standard of 4.6 µg/L as described in Section 3.3.2.2.2. Dissolved U, also derived in part from shale, is another constituent of increasing concern in the LARB. Loading of U in groundwater return flow contributes to measured values of C_U in the Arkansas River and its tributaries that often exceed the State and Federal standard of 30 µg/L, as discussed in Section *3.3.2.2.2*. Summaries of the spatial statistics of C_{Se} and C_U from routine groundwater samples for all sampling events over 2006 – 2011 in the USR and over 2002 – 2011 in the DSR are provided in Tables 3.20 and

3.21, respectively. The values of C_{Se} in samples from routinely monitored groundwater wells in the USR ranged from 0.1 to 1420 µg/L , averaging 55.5 µg/L. In the DSR, values of C_{Se} in routine groundwater samples ranged from 0.1 to 474 µg/L, averaging 33.1 µg/L. The 85th percentile values of C_{Se} in USR and DSR routine groundwater samples were 64.2 µg/L and 58.7 µg/L, respectively. For C_U in routinely monitored groundwater wells in the USR, values ranged from 4.9 µg/L to 972 µg/L, with an average of 73.6 µg/L and an 85th percentile of 111 µg/L. Values of C_U in routine groundwater samples in the DSR ranged from 1.0 µg/L to 907 µg/L, with an average of 107.1 µg/L and an 85th percentile of 165 µg/L.

Figure 3.44 shows a map of temporal-average C_{SeO_4} in groundwater in the USR predicted by a solute transport model of calibrated and tested using data from the USR over January 2006 – October 2009 (Bailey et al. 2014a, 2014b). In the USR, the overall spatial and temporal average value of C_{SeO_4} estimated using this model was 53.4 µg/L for the USR. Model estimates have not yet been completed for the DSR. Figure 3.45 shows the histogram of C_{Se} in samples from the groundwater monitoring wells in the USR over 2006 – 2011 and the DSR over 2003 – 2011. Also shown for reference in these plots is the 50 µg/L Colorado chronic standard value (85th percentile) for C_{Se} for livestock watering. Similar histograms for C_U are shown in Figures 3.46 for the USR and DSR. The 30 µg/L Colorado chronic standard value (85th percentile) for C_U for domestic water supply is shown in the plots.

The CV$_t$ values for C_{Se} in samples from groundwater monitoring wells over the study periods reveal substantial temporal variability. Values ranged from 0.07 to 2.28, averaging 0.81, in the USR and from 0.17 to 3.75, averaging 0.71, in the DSR. For C_U , values of CV$_t$ were more moderate. They ranged from 0.08 to 1.18, averaging 0.32, in the USR and from 0.07 to 0.82, averaging 0.24, in the DSR.

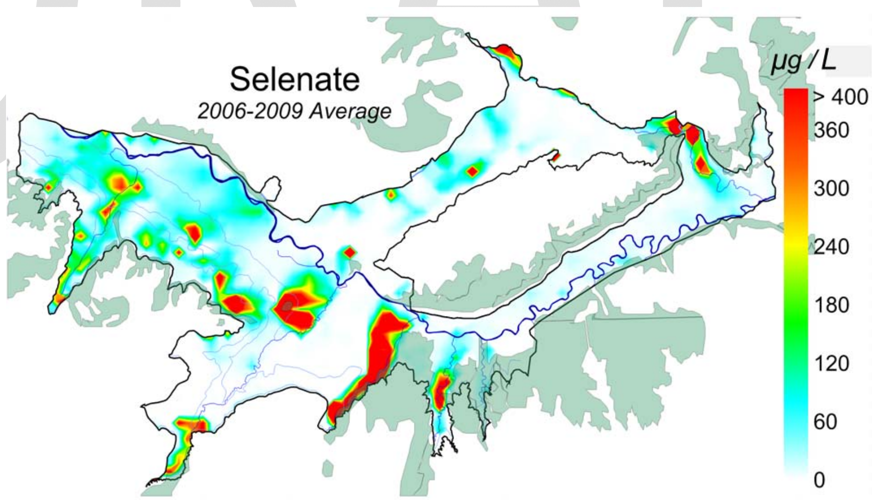


Figure 3.44. Map of average value of C_{SeO_4} simulated over January 2006 – October 2009 using a calibrated solute transport model (after Bailey et al. 2014b). The gray-green zones depict identified surface outcrops of marine shale.

Table 3.20. Statistical summary of C_{Se} and C_U in water samples gathered from groundwater monitoring wells within the USR.

Sampling Trip Description (Water Quality)				C_{Se} (µg/L)							C_U (µg/L)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile
158 (S1)	6/17/2006	6/20/2006	-	41	91.5	0.4	1360.0	2.64	5.7	69.8	40	88.3	9.3	436.0	1.12	21.6	142.6
170 (S2)	5/21/2007	5/24/2007	-	41	51.3	0.4	460.0	1.74	7.3	65.8	42	79.0	10.6	972.0	1.88	16.5	97.0
175 (S3)	10/6/2007	10/7/2007	52	35	62.9	0.4	1300.0	3.47	1.4	45.5	0						
178 (S4)	3/17/2008	3/22/2008	52	30	57.4	0.4	350.0	1.48	3.6	101.8	30	84.7	7.0	620.0	1.38	20.7	120.5
181 (S5)	6/21/2008	6/25/2008	-	74	33.5	0.4	218.0	1.40	3.0	55.2	74	75.4	2.4	603.0	1.19	18.3	111.5
184 (S6)	8/14/2008	8/15/2008	57	39	43.7	0.4	628.0	2.38	3.4	51.0	39	71.3	1.0	454.0	1.22	13.7	113.3
185 (S7)	1/15/2009	1/16/2009	51	30	48.6	0.4	253.0	1.30	1.9	116.5	29	77.6	9.7	282.0	0.82	26.3	113.6
186 (S8)	2/5/2009	2/5/2009	14	8	13.1	1.2	31.2	0.70	5.2	18.3	8	37.1	14.0	70.0	0.59	16.3	64.3
187 (S9)	5/13/2009	5/14/2009	52	34	46.6	0.4	321.0	1.64	6.7	62.5	34	76.3	7.9	704.0	1.63	11.8	104.1
190 (S10)	7/21/2009	7/23/2009	51	32	39.7	0.4	387.0	2.01	2.0	53.4	32	64.6	6.7	411.0	1.26	13.3	93.7
193 (S11)	11/19/2009	11/20/2009	51	31	73.2	0.4	1420.0	3.50	0.6	56.0	31	60.5	4.9	374.0	1.24	10.3	95.4
195 (S12)	3/12/2010	3/18/2010	-	29	65.1	0.4	910.0	2.63	0.7	68.7	29	76.9	9.5	290.0	0.86	17.2	124.0
196 (S13)	5/14/2010	5/16/2010	39	29	75.9	0.5	914.0	2.43	6.3	65.4	29	81.2	2.2	470.0	1.12	15.0	117.2
200 (S14)	7/20/2010	7/21/2010	50	35	26.6	0.4	210.0	1.34	6.2	40.0	30	59.7	8.9	207.0	0.76	14.7	94.3
201 (S15)	8/10/2010	8/13/2010	-	28	28.0	0.1	226.0	1.55	0.7	47.8	27	53.1	6.2	153.0	0.77	12.9	102.4
205 (S16)	5/20/2011	5/21/2011	36	18	101.7	1.2	1190.0	2.70	9.6	85.4	19	72.6	10.2	396.0	1.20	14.8	98.3

Table 3.21. Statistical summary of C_{Se} and C_U in water samples gathered from groundwater monitoring wells within the DSR.

Sampling Trip Description (Water Quality)				C_{Se} (µg/L)							C_U (µg/L)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile
27 (S1)	4/25/2003	5/4/2003	50	45	107.3	0.8	3560.0	4.91	7.6	51.9	0						
29 (S2)	5/29/2003	5/30/2003	-	17	13.1	1.1	38.0	0.81	2.4	21.0	0						
30 (S3)	6/3/2003	6/6/2003	-	8	24.0	13.8	46.7	0.46	15.3	30.0	0						
31 (S4)	6/10/2003	6/13/2003	-	19	218.1	0.6	3400.0	3.54	7.9	95.4	0						
33 (S5)	6/30/2003	7/3/2003	-	27	133.1	0.4	3150.0	4.53	3.1	29.3	0						
34 (S6)	7/7/2003	7/8/2003	-	17	37.0	1.5	152.0	0.99	11.1	56.4	0						
38 (S7)	7/27/2003	7/31/2003	-	42	97.5	0.4	2980.0	4.69	5.4	51.0	0						
45 (S8)	10/25/2003	11/2/2003	50	44	105.5	0.4	3440.0	4.89	6.5	48.0	0						
47 (S9)	1/12/2004	1/17/2004	-	47	102.0	0.4	3440.0	4.89	3.7	58.6	0						
49 (S10)	3/15/2004	3/19/2004	-	47	103.1	0.4	3560.0	5.01	7.4	57.7	0						
51 (S11)	4/30/2004	5/6/2004	-	46	111.6	0.7	3670.0	4.82	6.6	57.1	0						
54 (S12)	6/1/2004	6/4/2004	54	46	115.2	1.0	3690.0	4.69	6.2	66.2	0						
58 (S13)	6/28/2004	7/1/2004	-	48	110.5	0.7	3760.0	4.88	4.2	58.1	0						
62 (S14)	8/2/2004	8/6/2004	-	51	70.8	0.4	1710.0	3.42	2.7	78.3	0						
68 (S15)	11/4/2004	11/8/2004	54	50	25.9	0.4	144.0	1.19	3.6	47.3	0						
71 (S16)	1/10/2005	1/17/2005	-	50	27.1	0.4	158.0	1.26	4.3	42.4	0						
73 (S17)	3/15/2005	3/20/2005	-	48	25.8	0.4	166.0	1.34	4.4	40.6	0						
80 (S18)	6/27/2005	7/2/2005	-	49	29.1	0.4	162.0	1.25	3.3	50.8	0						
83 (S19)	7/19/2005	7/23/2005	-	49	27.6	0.4	152.0	1.17	3.1	45.6	49	90.9	11.0	580.0	1.09	25.6	154.0
86 (S20)	8/11/2005	8/19/2005	-	48	28.6	0.4	167.0	1.30	3.6	49.1	0						
89 (S21)	11/18/2005	11/22/2005	-	44	30.1	0.8	326.0	1.70	2.9	43.5	0						
91 (S22)	1/10/2006	1/13/2006	59	43	27.2	0.7	166.0	1.17	3.9	44.2	0						
94 (S23)	3/11/2006	3/15/2006	-	43	28.4	0.9	162.0	1.27	2.6	55.8	17	92.3	22.3	320.0	0.81	30.3	131.2
96 (S24)	5/13/2006	5/16/2006	60	47	31.0	0.4	170.0	1.35	2.9	47.7	47	107.0	16.6	811.0	1.19	32.6	174.6
100 (S25)	6/12/2006	6/15/2006	-	45	29.7	0.4	193.0	1.35	3.6	51.8	2	64.9	25.8	104.0	0.85	37.5	92.3
104 (S26)	7/11/2006	7/13/2006	-	48	34.5	0.4	228.0	1.39	2.3	58.8	0						
107 (S27)	8/7/2006	8/10/2006	-	44	36.5	0.4	199.0	1.31	3.3	71.9	0						

Table 3.21 (Cont.)

Sampling Trip Description (Water Quality)				C_{Se} (µg/L)							C_U (µg/L)						
Trip Number	Start Date	End Date	No. Wells Visited	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile	No. Tests	Average	Min	Max	CV	15th Percentile	85th Percentile
110 (S28)	11/18/2006	11/20/2006	61	47	32.2	0.4	182.0	1.30	2.6	68.7	1	23.5	23.5	23.5		23.5	23.5
113 (S29)	3/10/2007	3/11/2007	61	37	44.6	2.0	170.0	1.04	8.2	93.9	0						
116 (S30)	5/15/2007	5/18/2007	-	45	42.8	0.6	188.0	1.05	9.7	90.0	0						
119 (S31)	6/19/2007	6/22/2007	-	48	47.6	0.4	474.0	1.64	9.2	89.2	1	14.7	14.7	14.7		14.7	14.7
124 (S32)	7/22/2007	7/24/2007	-	41	40.9	0.4	186.0	1.11	7.2	83.4	0						
126 (S33)	8/13/2007	8/15/2007	-	46	38.0	0.4	192.0	1.19	6.0	82.0	0						
129 (S34)	11/17/2007	11/19/2007	60	47	39.5	0.4	423.0	1.72	6.2	63.7	0						
132 (S35)	1/15/2008	1/17/2008	61	41	44.5	0.4	466.0	1.80	5.9	72.6	41	118.6	22.2	744.0	1.17	36.9	165.0
136 (S36)	5/20/2008	5/21/2008	59	39	40.8	0.4	224.0	1.27	7.7	71.4	39	146.8	16.6	907.0	1.08	41.8	220.7
142 (S37)	7/12/2008	7/16/2008	46	34	21.3	0.4	96.6	1.03	4.0	31.6	34	94.5	18.2	370.0	0.76	28.4	157.2
146 (S38)	11/20/2008	11/20/2008	61	42	33.0	0.4	213.0	1.22	5.0	56.4	41	120.0	12.0	790.0	1.17	26.0	170.0
149 (S39)	3/13/2009	3/14/2009	61	36	37.8	0.4	376.0	1.69	6.1	54.8	36	111.6	20.0	840.0	1.23	40.5	147.5
152 (S40)	6/24/2009	6/25/2009	61	38	43.1	0.4	366.0	1.59	7.0	71.1	39	128.6	18.0	822.0	1.15	35.2	185.9
156 (S41)	8/27/2009	8/29/2009	60	33	27.8	0.4	134.0	1.01	7.4	48.8	34	92.1	16.4	268.0	0.71	32.8	147.2
158 (S42)	1/3/2010	1/7/2010	-	24	17.9	0.5	72.8	1.02	3.1	26.8	29	99.2	20.0	375.0	0.80	40.6	158.4
159 (S43)	3/13/2010	3/16/2010	-	28	22.6	0.4	87.9	0.97	5.0	29.6	28	98.2	19.0	260.0	0.72	38.2	179.5
161 (S44)	6/8/2010	6/9/2010	48	28	32.7	0.9	218.0	1.35	8.2	64.7	28	108.7	22.9	362.0	0.84	33.9	165.6
164 (S45)	8/10/2010	8/11/2010	-	24	28.8	0.4	180.0	1.28	7.3	49.2	24	88.0	1.0	386.0	0.90	33.0	144.6
168 (S46)	5/18/2011	5/19/2011	48	28	45.8	0.1	320.0	1.60	7.5	59.0	28	113.8	8.3	373.0	0.77	45.5	185.9

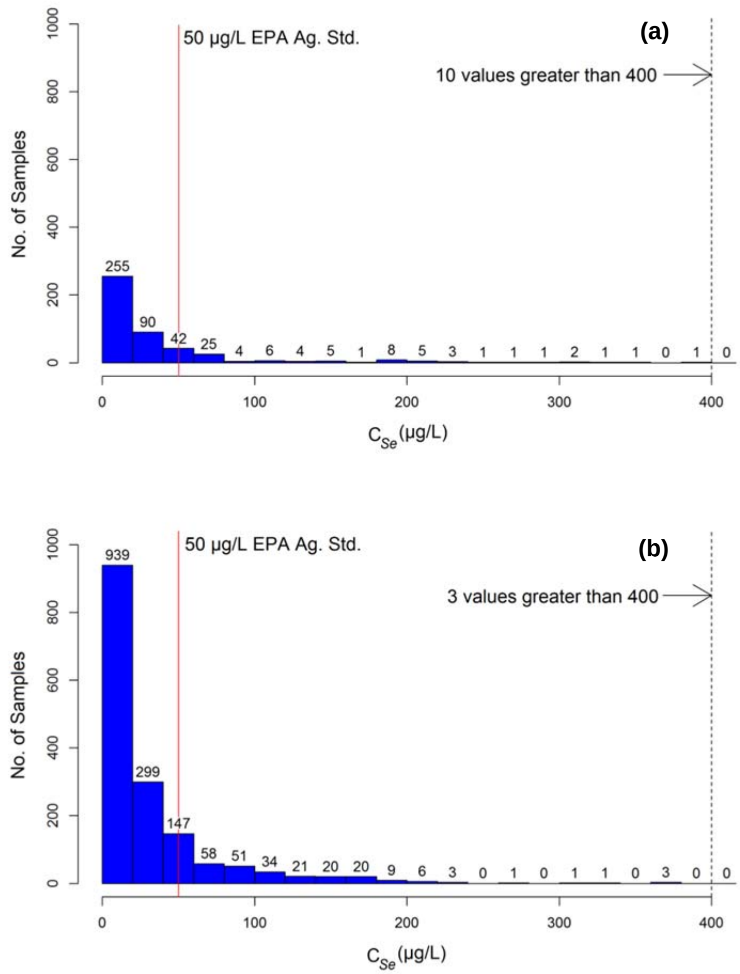


Figure 3.45. Histograms of all C_{Se} values in water samples from all routinely-sampled groundwater monitoring wells within the (a) USR and (b) DSR during the study periods. The red vertical line shows the livestock watering standard of 50 µg/L (85th percentile value).

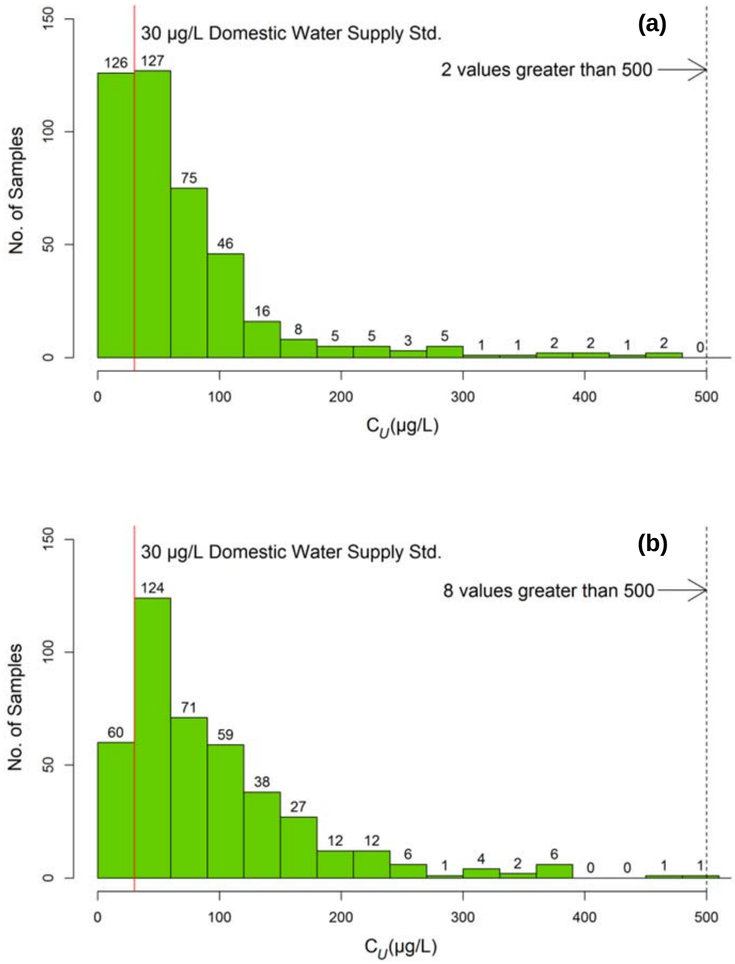


Figure 3.46. Histograms of all C_U values in water samples from all routinely-sampled groundwater monitoring wells within the (a) USR and (b) DSR during the study periods. The red vertical line portrays the chronic domestic water standard of 30 µg/L (85th percentile value).

3.3.4.2.4 Correlation and Relationships between Dissolved Constituents in Groundwater in the LARB Study Regions

Tables A3.23 and A3.24 in Excel File AJ the ARBhwq CD provide a summary of the statistically-significant ($\alpha = 0.05$) Pearson correlation coefficient values computed over the considered paired relationships between water quality variables X and Y (X-Y, ln X-Y, ln X-ln Y, and X-ln Y) measured in groundwater monitoring wells in the USR and the DSR, respectively. Similar to the surface water samples, many moderate to high correlations between the various ions are found in these results.

Least-squares regression relationships were developed between TDS and EC for groundwater samples collected in the USR and the DSR and are shown in Figure 3.24 along with similar relationships developed for surface water. The R^2 values shown on the plots are statistically significant

($\alpha = 0.05$). The difference in the relationships for groundwater in the USR and groundwater in the DSR likely is due to the different ionic composition of the water as discussed in Section *3.3.4.2.1*.

The non-linear relationships between C_{Se} and C_{NO_3-N} in groundwater samples in the USR and DSR are depicted in Figure 3.47, which shows the observed data plotted along with statistically-significant regression equations ($\alpha = 0.05$). These relationships are indicative of the effect of NO_3 in oxidative dissolution of Se from marine shale in the valley of the LARB and in inhibition of the chemical reduction of SeO_4 and SeO_3 (Gates et al. 2009, Bailey et al. 2012). A related finding is that the average CV_t of C_{Se} in samples from groundwater monitoring wells over the study periods is two to five times greater than CV_t values for all other measured ion concentrations except C_{NO_3-N} in the groundwater monitoring wells. Like CV_t of C_{Se}, CV_t of C_{NO_3-N} also is relatively high at 0.95 in the USR and 0.71 in the DSR, which is possibly another indicator of the dependence of C_{Se} on C_{NO_3-N} through oxidation-reduction reactions.

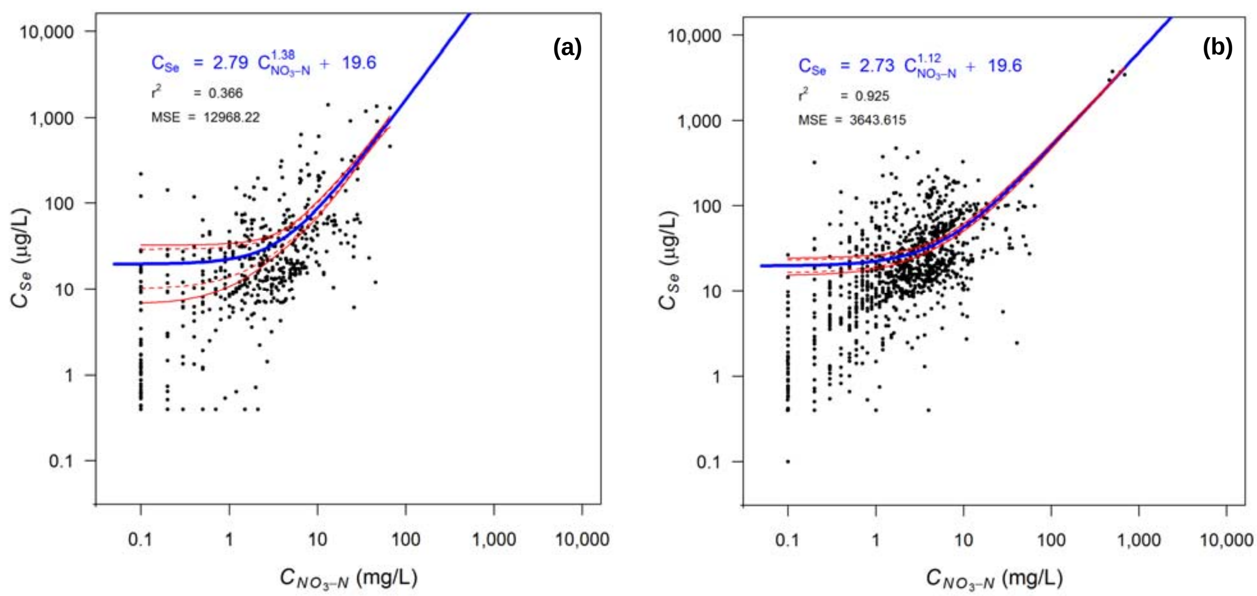


Figure 3.47. Data and regression relationships between C_{Se} and C_{NO_3-N} in water samples from groundwater monitoring wells in (a) the USR and (b) the DSR. The red dashed lines and the solid red lines indicate the 85% and 95% confidence intervals for the regression curve, respectively.

3.3.4.3 Mass Loading of Groundwater Dissolved Chemicals to the River in the LARB Study Regions

Estimates of daily rates of unaccounted-for mass loading to the Arkansas River were computed for June 2005 to December 2011 in the USR and DSR. These loading estimates include loads to or from the river by groundwater flow, ungaged tributaries, and overland flow. However, they are thought to be primarily due to groundwater flow, especially in the non-irrigation season. Summary temporal statistics over the considered periods for some important constituents are shown in Tables 3.22 and 3.23 for the USR and DSR, respectively. These loads constitute a substantial contribution to the total instream loads in the river. Their impact on instream concentrations is currently under investigation.

Table 3.22. Temporal statistics of estimated loading rates of selected dissolved constituents to the Arkansas River within the USR during June 2005 – December 2011.

Loading Rate (lb/day per mile)						
Constituent	Min	15th Percentile	Mean	85th Percentile	Max	CV
BiCarbonate	-6386	1242	3388	5698	13986	0.69
Calcium	-4311	1440	3183	4942	12003	0.57
Magnesium	-4311	1497	3356	5283	12351	0.58
Nitrate-N	-89	4	18	35	99	1.04
Sodium	-2895	1519	2899	4357	9392	0.50
Sulfate-S	-6060	2072	4329	6965	15725	0.57
Selenium	-0.43	0.04	0.14	0.28	0.78	0.87

Table 3.23. Temporal statistics of estimated loading rates of selected dissolved constituents to the Arkansas River within the DSR during June 2005 – December 2011.

Loading Rate (lb/day per mile)						
Constituent	Min	15th Percentile	Mean	85th Percentile	Max	CV
BiCarbonate	-10126	1153	2292	3534	17924	0.69
Calcium	-4754	1277	2398	3612	16534	0.62
Magnesium	-4456	507	1153	1898	8334	0.81
Nitrate-N	-43	4	11	18	64	0.99
Sodium	-4925	1990	3541	5216	21022	0.55
Sulfate-S	-7575	2650	4747	7107	30445	0.57
Selenium	-0.25	0.11	0.21	0.28	0.99	0.63

Figures __ and ___ show example time series plots of unaccounted-for mass loads of Se and selected constituents to the Arkansas River in the USR and DSR, respectively.

Chapter 4

Conclusions

Extensive field investigations in three study regions within Colorado's Arkansas River Basin have been described in this report. The studies address selected hydrologic and water quality characteristics over 2009 – 2011 in a region of the UARB and over 1999 – 2012 and 2002 – 2012 in two respective regions of the LARB. The findings expose key features of surface water and groundwater and provide information central to the development and application of computational models and a planned Arkansas River Decision Support System to assist with improved water management.

4.1 Conclusions for Upper Arkansas River Basin in Colorado

Flow rates in the Arkansas River and its major tributaries in the UARB study region in Chaffee County, Colorado during the study period reflect levels near or slightly less than the historic long-term averages. From Granite to Wellsville, the Arkansas River average daily flow is found to increase by 83% and 122%, during irrigation and non-irrigation seasons, respectively. The measured tributaries within this reach contribute approximately 60% and 45% of the percent increase in the respective seasons. The remaining unaccounted-for sources of increased flow, including groundwater discharge, irrigation return flows in surface drains, other unmeasured tributaries, and overland flow and direct precipitation, contribute a daily average of about 2.7 and 2.2 ft^3/s per mile along the river in irrigation and non-irrigation seasons, respectively. Long-term trends of unaccounted-for contributions to river flow dynamics suggest an annual oscillation cresting in November at about 3.7 ft^3/s per mile and reaching a minimum in May of around 0.2 ft^3/s per mile. Groundwater flow is likely the largest contributor to non-tributary accretions along the river. Water table monitoring and canal seepage test results generally support this conclusion, providing evidence of a strong relationship between irrigation activities, aquifer storage levels, and subsequent groundwater discharge to the river.

Canal seepage tests in the Riverside Allen, Cottonwood Maxwell, and Salida canals reveal significant seepage rates. On average, the canals lose water to the adjacent vadose zone at a rate of 1.2 ft/day (range of 0.6 to 1.5 ft/day) through the wetted perimeter area. This rate likely represents the magnitude of seepage from irrigation canals throughout the study region and supports the substantial role that irrigation plays in the pattern of recharge to the alluvial/outwash aquifer.

Groundwater monitoring wells in the alluvial/outwash aquifer show water table depths ranging from 0 to 65 ft below the ground surface with an average depth of 21 ft. The within-year variability across the groundwater-monitoring network exhibits a peak water table level around the same time as the hydrograph peak in surface waters. The lowest water table levels occur in April and May, just prior to rising hydrographs from snowmelt runoff. These low levels occur during the initiation of irrigation water applications (starting around April 15) but before water table levels show affects from irrigation recharge to the aquifers. Overall, the groundwater table is consistently shallow during the summer months but with variability that suggests irregular outside influences. Around late October, after the end of irrigation season, the erratic variability changes to a smooth decrease in which average water table levels drop off slowly in the fall and winter season. In the Spring, the average water table level shows a relatively abrupt increase from the winter minimum level to the higher summer average level. Water table levels in monitoring wells with confirmed irrigation influence show the largest seasonal change, with an average range of 7 ft above and below the mean level.

Average hydraulic conductivity values in the alluvial/outwash aquifer are in the range of 20 to 30 ft/d for both seasonal tests and across the three analytical techniques used. These hydraulic conductivity values (calculated from slug tests in groundwater monitoring wells) are at the lower end of the published ranges for the known geology in the UARB study region and are less than 25% of the value estimated by a 2008 aquifer test.

Overall, solute water quality at sampled surface water and groundwater sites in the UARB study region is very good for the constituents tested. Surface and groundwater samples predominantly exhibit a calcium-bicarbonate solute composition type. In-situ measurements of EC, pH, DO, ORP, and *T* at surface water sites are within expected ranges and typically meet all regulatory levels for human and livestock use as well as aquatic life purposes. In-situ measurements at groundwater sites also exhibit good water quality with some instances of pH readings below recommended consumption limits. DO levels in groundwater were high, with an average of about 6.2 mg/L. These elevated DO levels are likely a result of short residence times and the aquifer geology where microbial respiration and decomposing organic matter is limited, resulting in high-sustained DO levels from the original recharge sources (Rose and Long 1988).

Values of average TDS concentrations at surface water (93.4 mg/L) and groundwater (202.9 mg/L) monitoring locations are well below the EPA drinking water limit (500 mg/L). The highest average TDS concentration (312 mg/L) was measured in the southeastern most monitoring well, while the lowest average value (86 mg/L) occurred in the northernmost well. Water quality, generally represented by TDS, degrades downstream due to reduced high-quality precipitation (snowmelt and rain runoff), increased anthropogenic uses and effects, evaporative concentration, and accumulation of dissolved minerals. Seasonally, peak snowmelt runoff volume dilutes the accumulation of dissolved constituents and results in higher water quality. During low-flow seasons, groundwater baseflow with higher TDS concentration results in lower water quality in streams.

Data were grouped to develop relationships for estimating TDS from in-situ EC measurements for surface water and groundwater in the study area. Using EC-TDS relationships and measured values of EC and Q, a relationship between TDS and Q was developed for each of the three river monitoring sites using power function regression analysis. The Q-TDS regression equations are more reliable at low discharge levels where more observations are available, but allow for a comprehensive estimate of annual TDS mass loading and temporal trends of loading through the system.

Mass loading of TDS increases in the Arkansas River moving downstream through the study region, but greater than half of the relative increase is provided by sources other than the monitored tributaries. Over the study period, the TDS mass load flux increases by an average of 114% from Granite to Salida. During the irrigation and non-irrigation seasons the load increased by 102% and 112%, respectively. Peak TDS load increase occurs in periods that are generally consistent with those identified with the peak of unaccounted-for sources and with the observed non-irrigation season draining of the aquifer as seen by water table level decreases. This increase suggests the significance of groundwater TDS mass loading to the system during low surface flow conditions.

Laboratory water quality analysis of 143 surface water samples show minimal presence of selenium and some little presence of uranium, increasing in concentration moving downstream and with some elevated levels in the lower reaches of the South Arkansas River and Browns Creek, yet still well below regulatory limits. Some locations show elevated levels of manganese, perhaps worthy of continued sampling for this constituent. A large lead concentration from late-season base-flow conditions in upper Clear Creek also may be worthy of some continued monitoring. Analyses of 135 groundwater samples indicate good water quality, but the data support possible continued monitoring of uranium, manganese, and fluoride.

In summary, groundwater and surface water monitoring in the UARB study region provides data which, although representative of a short time period, are helpful in understanding and quantifying their interdependent relationship along with the influence of irrigation water application on the alluvial/outwash aquifer. Groundwater table levels in the aquifer appear to be significantly affected by irrigation recharge with residual effects for months following the end of irrigation activities, and groundwater flow to the river system seems appreciable along the study reach. Capturing these processes will be important to the development of models for exploring alternative water management futures for the UARB. Water quality in the UARB study region is quite good; however, concentrations of selected constituents in some locales give reason for some on-going attention.

4.2 Conclusions for Lower Arkansas River Basin in Colorado

Studies in the LARB were conducted in two regions of the irrigated valley during periods of Arkansas River flow that spanned from very wet in 1999 (183% of the long-term average) to extremely dry in 2002-2003 (20 to 25% of the long-term average) but generally exhibited below-average hydrologic conditions. Within the study periods, flow diversions from the Arkansas River to major canals in the USR and DSR study regions were 11% and 16%, respectively, below the 1985 – 2012 average, indicating irrigation water supply conditions that were a bit below average. Groundwater return flows to the Arkansas River in the USR, estimated from water balance analysis, average about 2.8 ft^3/s per mile along the river during the irrigation season and 0.8 ft^3/s per mile during the non-irrigation season. In the DSR, they average about 1.4 ft^3/s per mile and 1.2 ft^3/s per mile during the irrigation season and non-irrigation season, respectively.

Canal seepage, in addition to deep percolation from excess irrigation, makes a major contribution to the patterns of recharge to the valley aquifer. Canal seepage estimated from seven inflow-outflow tests on three canals in the LARB in 2011 ranged from 0.24 to 0.90 ft/day through the wetted perimeter area. These loss rates are substantial and comparable to values of -0.6 ft/day (gain) to 3.4 ft/day reported elsewhere by CSU. These findings underscore the importance of accurately representing the temporal and spatial distribution of canal seepage patterns for use in current and future models of groundwater and surface water flows in the LARB valley.

The groundwater table in the LARV was found to be quite shallow during the study periods with reported average measured depths in groundwater monitoring wells ranging from 2.5 ft to 26.0 ft in the USR and from 3.1 ft to 51.1 ft in the DSR. Estimates using models calibrated with the data presented here indicate irrigation-season average water table depths over the USR and DSR study regions of about 15 ft and 22 ft, respectively. As was found in the UARB, water table levels display a significant seasonal variability in the LARB, dropping to their lowest elevations in late winter and rising to their highest levels in mid to late summer. Over the study periods, the highest water tables (smallest depths) were recorded during and immediately following 1999, which was a relatively wet year. The lowest levels (highest depths) tended to occur in 2004 or 2005, which was after an extended drought period that began in 2002.

In stark contrast to findings from the UARB study region, EC and TDS in the sampled Arkansas River reaches in the LARB are quite high. Average values of TDS are about 930 mg/L in the USR and 2,930 mg/L in the DSR. These values are 10 to 30 times the average TDS measured in the headwaters study region in the UARB, posing a high hazard to irrigated crops and markedly exceeding the EPA drinking water limit. Values exceeding 4,000 mg/L are measured near the Colorado-Kansas border during the winter season. The makeup of the dissolved solute ions in the LARB reveals a calcium/sodium-sulfate composition with the sodium cation growing in prominence downstream along the Arkansas River. Mass balance calculations using available stream and canal flow records along with water quality data permit approximation of the loading of major salt ions to the Arkansas River. Mass loading of TDS in unaccounted-for return flow (groundwater and ungaged surface flow) is estimated to occur at an average rate of about 12 tons/day per mile along the Arkansas River in both the USR and DSR.

In groundwater, average values of EC and TDS are about 3 and 1.5 times the average values of EC and TDS observed in the Arkansas River during the irrigation season in the USR and DSR, respectively, reflecting the effects of evaporative concentration along with biogeochemical reactions. The high surface water and groundwater salinity in the LARB regions contribute to the high soil water salinity values and reduced crop yields reported elsewhere (Morway and Gates 2012).

Like surface water samples, groundwater samples in the LARB reveal calcium/sodium-sulfate type waters with the sodium cation growing in prominence in the downstream direction. Statistically significant linear regression relationships between TDS and EC are reported for surface water and groundwater in both regions of the LARB, with TDS per unit value of EC being about 30% and 20% higher in the USR and DSR, respectively, than in the UARB. This increase likely reflects the differing salt ion composition.

Selenium proves to be a serious and ubiquitous problem in the Arkansas River in the LARB, amounting to between 2.5 and 3.0 times the chronic concentration standard for aquatic life in the USR and between 1.4 and 3.7 times in the DSR. Groundwater concentrations, averaged over the study periods in the USR and DSR, are about 56 μg/L and 33 μg/L, respectively. These selenium concentrations are strongly correlated to nitrate concentrations, likely indicating nitrate's role in dissolving selenium from subsurface shale formations and in inhibiting its chemical reduction as it returns to the river system. The rate of return in the USR and DSR is estimated as 0.14 and 0.21 lbs/day per mile along the river, respectively.

Though not as severe as selenium, uranium concentrations measured in the river also are high. Values (85^{th} percentile) are multiples of 0.7 to 1.2 times the chronic standard for drinking water along the Arkansas River in the USR and 0.8 to 2.6 in the DSR. Also, measured nitrate nitrogen concentrations confirm a concern about nutrient pollution in the LARB. The 85^{th} percentile sample value exceeds the interim standard of 2 mg/L for total nitrogen (nitrate plus nitrite plus ammonium) at 9 out of 11 sample locations along the Arkansas River in the USR and 2 out of 8 locations in the DSR.

In summary, studies in the LARB reveal a shallow groundwater aquifer and stream-interactions that are strongly influenced by recharge from irrigation practices, including canal seepage. Dissolved solute concentrations in the stream-aquifer system are rather variable in space and time but generally quite high. Salt concentrations, measured by TDS, are at levels that threaten crop productivity and substantially exceed drinking water standards. Selenium and uranium concentrations exceed current chronic standards in the river system, and nitrate concentrations are on the border of interim standard violation.

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